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RESEARCH MEMORANDUM

LOW-PRESSURE PERFORMANCE OF EXPERIMENTAL PREVAPORIZING TUBULAR COMBUSTOR USING APPROXIMATELY STOICHIOMETRIC ADMISSION OF FUEL-AIR MIXTURE INTO THE PRIMARY ZONE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

An experimental tubular combustor, in which approximately stoichiometric prevaporized fuel-air mixtures were introduced into the combustor primary zone, was developed and tested to determine whether improved performance could be obtained with this type of fuel-air admission. The fuel was vaporized on the outer surface of the primary-zone liner and introduced into the primary zone with sufficient air to form these mixtures. The combustor was tested with MIL-F-5624B grade JP-4 fuel under conditions simulating flight at high altitude. Its performance was compared with that obtained with a current production tubular combustor of the same diameter.

At 100 feet per second reference velocity, the experimental combustor gave maximum combustion efficiencies of 95 and 88 percent at combustor-inlet pressures of 15 and 8 inches of mercury absolute, respectively. This combustor, when tested at these and other conditions of inlet pressure and reference velocity, yielded efficiencies higher than those obtained with a production model. The experimental combustor also gave indications of having a low tendency to form carbon. However, operation was limited in that flame would flash back into the vaporizing area under conditions of low air velocities or high combustor-inlet pressures.

INTRODUCTION

A general research program is currently in progress at the NACA Lewis laboratory to determine design criteria for improving performance of turbojet combustors. As a part of this program, research was conducted to investigate prevaporized stoichiometric fuel-air admission in a tubular combustor operating at low inlet air pressures and at higher air-flow rates than those used in current production combustors.

The operating region of a turbojet combustor is so over-all fuel-lean that burning would be impossible if the fuel and all the air were premixed prior to ignition. Burning is possible only because a flammable fuel-air ratio is maintained in a sheltered primary zone. In current practice, fuel is introduced into the primary zone as either a liquid spray (atomizing combustors) or as a very rich fuel-air mixture (prevaporizing combustor). The necessary quantity of air to provide flammable mixtures is admitted separately, and the fuel and air mix within the combustor zone. With current production combustors, operation is possible at pressures of 1/2 atmosphere or less, and at linear velocities of the order of 100 feet per second; however, combustion efficiencies substantially less than 100 percent are obtained under these conditions. There is also a tendency of the combustor to form objectionable carbon deposits and smoke at high pressures with some types of fuels.

Since such fundamental combustion properties as minimum pressure limits for flammability, flame velocity, and quenching distance are optimized at fuel-air ratios near or slightly rich of stoichiometric for low-molecular-weight hydrocarbon-air systems (refs. 1 to 3), it appeared that combustor performance also might be optimized if approximately stoichiometric quantities of fuel and air were mixed and then introduced into the combustion zone. Improvement might also be realized in the coking and smoking tendencies of the combustion chamber since carbon deposits and smoke can be formed only in fuel-rich regions (ref. 4), and the elimination of these should in turn eliminate combustor carbon and smoke, irrespective of fuel quality.

The use of approximately stoichiometric fuel-air admission presented the problems of (1) maintaining a nearly constant fuel-air ratio input to the primary zone over the wide range of over-all fuel-air ratios required for engine operation, (2) vaporizing the fuel without excessive metal surface areas or metal temperatures, (3) maintaining a steady, nonsurging supply of vaporized fuel, and (4) avoiding a possible fouling of the vaporizer surface. In spite of these difficulties, this investigation was conducted to determine whether an experimental combustor having approximately stoichiometric fuel-air admission could be designed which would provide improved performance characteristics at high-altitude operating conditions. The investigation was made in a direct-connect duct with a 9.5-inch-diameter tubular combustor. MIL-F-5624B grade JP-4 fuel was used, and the operating conditions investigated were representative of severe conditions in current engines.

This report describes the development and performance of the experimental combustor. Data are presented that illustrate the effect of combustor liner design on the outlet-temperature profile and the effect of air mass flow to the combustion zone on combustion efficiency. A final combustor configuration was tested at five conditions simulating severe

altitude conditions, and the results were compared with those obtained with a production combustor of the same diameter. The results presented herein are primarily concerned with combustion efficiencies at low pressures, and only an indication of the carbon-forming characteristics of the combustor is given.

APPARATUS AND PROCEDURE

Installation

A diagram of the test facility is shown in figure 1. Combustor-inlet and -outlet ducts (6-in. diam.) were connected to the laboratory air supply and altitude-exhaust facilities. Air-flow rates and combustor pressures were regulated by remotely controlled valves located upstream and downstream of the combustor. The inlet air was preheated by a steam-fed exchanger. The connections between the ducts and combustor were made through conical inlet and outlet diffusers $15\frac{1}{2}$ and 5 inches long, respectively.

Instrumentation

Air was metered through square-edged orifices installed upstream of the regulating valves (fig. 1) according to A.S.M.E. specifications. Fuel-flow rates were measured by calibrated rotameters. Combustor-inlet total pressures and temperatures were measured by pressure probes and bare-wire chromel-alumel thermocouples at station 1 (fig. 1); combustor-outlet total pressures and temperatures were measured by pressure probes and bare-wire chromel-alumel thermocouples at stations 2 and 3, respectively (fig. 1). Temperatures and total pressures were measured at the duct positions indicated in figure 2. The inlet thermocouples and all pressure probes were stationary. The seven outlet thermocouple probes at station 3 were moved radially by means of a chain-driven mechanism (ref. 5) to positions representing centers of four equal annular areas (fig. 2(c)). Sketches of the pressure probes and thermocouples are presented in figure 3. The thermocouples were connected to a self-balancing, direct-reading potentiometer. The outlet thermocouples were connected in a parallel circuit to give an instantaneous average temperature at each of the four fixed radial positions. The pressure probes were connected to absolute manometers.

Combustor

The principal features of the tubular combustor used for this investigation are shown diagramatically in figure 4. The cylindrical housing had an inside diameter of $9\frac{1}{2}$ inches and was $28\frac{1}{4}$ inches long.

The distance from the downstream end of the starting nozzle to the plane of the outlet thermocouples was $32\frac{1}{2}$ inches. The throat and throttling device shown in figure 4 controlled the ratio of primary to secondary air. A small portion of the primary air entered the upstream end of the primary through a swirl plate, but most of the primary air passed along the outside of the flame tube where it mixed with vaporizing fuel prior to entering the primary combustion zone. The secondary air passed through the outer annulus and entered the combustor through an interchangeable punched sleeve. Four secondary sleeve configurations were tested. The results of these tests are described in the RESULTS AND DISCUSSION.

A split fuel-feed system was used, as shown in figure 4. An atomizing nozzle (30° hollow cone nozzle rated at $2\frac{1}{2}$ gal/hr at 100 lb/sq in. pressure differential), required for starting, was installed in the upstream end of the primary flame tube. The remainder of the fuel was vaporized along the outer walls of the primary and required a multiple feed to this surface to assure even circumferential distribution of the fuel. A simple orifice-type manifold was impractical for this purpose, since the small orifices required would be susceptible to clogging. Therefore, the capillary-type manifold shown in figure 4 was made, consisting of thirteen 7.0-foot lengths of 0.032-inch-inside-diameter stainless tubing silver-soldered on equal angular spacings to a manifold header made from an 8-inch-diameter ring of 3/16-inch-inside-diameter tubing. The discharge ends of the capillaries were clamped to the outer upstream end of the primary with equal circumferential spacing. After the fuel left the capillaries, the circumferential distribution of the fuel was controlled by 13 fences, each 1/4 inch high and 5 inches long running longitudinally down the outer walls of the primary. The fuel was further confined and kept in close contact with the primary outer walls by a cylindrical shroud fitted over the fences. These fences and the shroud are shown in figure 4. Two alternate fuel-injection systems were used briefly during this investigation. A capillary feed system with 18-inch lengths of 0.040-inch-inside-diameter capillary was used to meet the higher fuel-flow requirements for one test condition, and for the few tests on atomized fuel alone, a $7\frac{1}{2}$-gallon-per-hour (rated at 100 lb/sq in. differential) 80° nozzle was used in place of the smaller-capacity starting nozzle.

A conventional aircraft spark plug with extended electrodes was used for ignition. Also, two sight glasses were installed in the combustor housing to permit limited views of both the primary and secondary regions of the combustor.

Fuel

The fuel used in this investigation was MIL-F-5624B grade JP-4 supplied from the laboratory distribution system. Representative inspection data for this fuel are presented in table I.

Test Conditions

Since it was desirable that the combustor be tested in the same environment that would be encountered in an engine during flight at high altitudes, the following conditions of combustor-inlet pressures, temperatures, and air flows were selected as standard test conditions. Equivalent flight altitudes and engine speeds for a 5.2-pressure-ratio engine operating at 0.6 Mach number flight speed are also listed for these conditions:

Condition	Combustor-inlet conditions			Equivalent flight conditions	
	Pressure, in. Hg abs	Air flow, lb/(sec)(sq ft)	Temperature, °F	Altitude, ft	Rotor speed, percent rated
A	15	2.78	268	56,000	85
B	8	1.49	268	70,000	85
C	5	.93	268	80,000	85
D	15	2.14	268	56,000	85
E	15	3.62	268	56,000	85

Conditions A, B, and C represent combustor-inlet conditions for a given engine operating at constant rotor speed at varying altitudes. Conditions A, D, and E represent conditions of varying specific air flows that would result from the use of a given combustor with compressors of varying air-handling capacities. Pressure ratio and altitude are held constant in the latter case.

Limitations in altitude exhaust and inlet air preheating capacities in the test facility required some compromise in operating pressures and temperatures. The following conditions were those actually attained during this investigation:

Condition	Pressure, in. Hg abs	Air flow, lb/(sec)(sq ft)	Temperature, °F
A	15	2.78	240 to 250
B	8	1.49	215 to 230
C	6	.93	210 to 220
D	15	2.14	240 to 255
E	15.3 to 17.5	3.62	255

Runs were also made under the following conditions to (1) simulate mild operating conditions and (2) test the carbon-forming tendencies of the combustor:

Condition	Pressure, in. Hg abs	Air flow, lb/(sec)(sq ft)	Temperature, $^{\circ}F$
F	21-22	1.49	220
G	60	11.25	250

Test Procedure

Combustor temperature-rise data were obtained for a range of fuel-air ratios at the test conditions listed. Combustor pressure-loss data were also determined in some test runs.

Combustion efficiency, defined as the percentage ratio of actual to theoretical increase in enthalpy of gases flowing through the combustor, was computed by the method of reference 6. The average combustor-outlet temperature was used to calculate the enthalpy of gas at the combustor outlet. Thermocouple indications were not corrected for velocity or radiation effects. Some indication of the accuracy of the combustion efficiencies calculated in this way may be found in the following comparison of these efficiencies with those determined by exhaust-gas analysis. Three exhaust-gas samples were taken from this test facility, and the combustion efficiency was determined by the method of reference 7.

Sample	Efficiency, percent, calculated from	
	Enthalpy change	Gas analysis
1	94	96
2	94	94
3	83	85

While the absolute accuracy of neither method is known, the agreement between the two independent methods suggests that the combustion efficiency data presented herein are reasonably good.

Combustor reference velocities were computed from the air-flow rate per unit combustor cross-sectional area and the combustor-inlet air density. Combustor total-pressure losses are expressed as the dimensionless ratios of (1) combustor total-pressure loss to a reference velocity pressure based upon combustor reference velocity and inlet air density, and (2) combustor total-pressure loss to combustor-inlet total pressure.

RESULTS AND DISCUSSION

Combustor Development

In the following discussion, the evolution of the final combustor configuration is described with respect to (1) secondary sleeve development, (2) primary air control, and (3) primary-zone mixture introduction. This is followed by the presentation and discussion of the performance data for the final combustor configuration.

Secondary sleeve configurations. - The first phase in the development of the experimental combustor was to obtain a satisfactory outlet-temperature profile through control of the secondary air admission. The four secondary sleeve configurations diagrammed in figure 5 were tested at condition A at an average outlet temperature of about 1200° F, using the primary zone configuration and split fuel-feed system shown in figure 4. Average circumferential outlet temperatures at each of four radial positions were measured. These temperatures are shown in figure 6 as a function of radial position in the duct for each of the secondary sleeves tested. Configuration M-1 used holes and louvers and gave a very hot core with center duct temperatures averaging over 1000° F hotter than the average near the wall. Configuration M-2 was the same as M-1 except that additional holes were punched upstream, and the downstream ring of holes was opened up to form slots. These changes produced no appreciable improvement in outlet-temperature profile. Configuration M-3 had substantially the same open area as M-1 but used 4-inch slots in place of holes and gave a much better outlet-temperature profile than did M-1. Configuration M-4 used a slightly different array of slots and produced a satisfactory temperature profile. In general, the use of slots gave substantially improved temperature profiles, probably because the slots provided deeper penetration of the secondary air. Configuration M-4 was used as the secondary sleeve for the remainder of this investigation.

Primary air control. - As shown in figure 4, the ratio of primary to secondary air could be controlled at the upstream end of the combustor housing by means of a remotely controlled plunger moving axially. Although the fraction of the total air entering the primary zone was not known as a function of throttle position, the effects of changing primary air flow on combustion efficiencies could be qualitatively determined. Figure 7 shows the effect of varying primary air flow at constant total air flow on combustion efficiencies obtained at condition A with varying over-all fuel-air ratios. With low primary air flows, maximum efficiencies were obtained at low over-all fuel-air ratios and efficiencies decreased rapidly with increasing fuel-air ratio. With high primary air flows, better results were obtained with rich than with lean over-all fuel-air ratios. Intermediate primary air flow gave intermediate results.

The effects of primary air flow on combustion efficiency can be explained as follows: Restricting the primary air both increases the primary-zone fuel-air ratio and reduces the linear velocity in this region, a condition conducive to best performance at very lean over-all fuel-air ratios. However, with increasing fuel flow, the primary zone soon becomes overrich and efficiencies decrease rapidly. Conversely, increasing the primary air flow increases the linear velocity and, at low fuel rates, may result in an over-lean primary. However, as over-all fuel-air ratio is increased, the primary-zone fuel-air ratio increases to more nearly optimum conditions for combustion. The results shown in figure 7 illustrate the compromises that must be made to obtain adequate performance in a fixed-geometry combustor over a wide range of over-all fuel-air ratios.

Subsequent changes in the vaporizer outlet moved the principal throttling point from the plunger-throat region to the vaporizer-outlet region. Therefore, the plunger-throat primary air control became of minor importance and, for the data presented hereinafter, the plunger was left in the fully withdrawn position exposing the maximum throat area.

Introduction of the fuel-air mixture into the primary zone. - The outlet section of the vaporizer (fig. 4) was initially punched with two rows of 7/8-inch-diameter holes for fuel-air mixture admission into the primary zone. However, preliminary visual observation indicated a possible lack of circulation of the incoming mixture into the primary zone; therefore, the holes were subsequently replaced with 13 directional tubes, 3/4 inch long with 5/8-inch inside diameters, which were inclined upstream at an angle of 71° from the burner axis. This change resulted in improved efficiency and was adopted for the final combustor configuration shown in figures 8 and 9. General arrangement of most of the combustor components is presented in figure 8, and pertinent dimensions are shown in figure 9. All data presented hereinafter were obtained with the combustor configuration described in these figures.

Combustion Efficiency of Final Configuration

Performance data obtained with the final combustor configurations are presented in table II, where combustor-inlet conditions, fuel flows, fuel-air ratios, inlet and outlet temperatures, and combustion efficiencies are listed. Preliminary testing of this configuration showed that combustor stability and efficiencies were generally improved by the use of some atomized fuel from the pilot nozzle. Most of the data shown in table II were obtained using varying amounts of pilot nozzle and vaporized fuel flows, and these quantities are listed in the table.

Effect of partition of fuel between pilot nozzle and vaporizer. - Combustion efficiency obtained at any given test condition and fuel-air ratio was influenced by the partition of fuel flow between the pilot nozzle and the vaporizer. This effect is shown for test conditions B and C in figure 10, where combustion efficiencies are plotted against the pilot fuel flow expressed as the percentage of total fuel injected for narrow ranges of over-all fuel-air ratios. It is apparent from this figure that at low over-all fuel-air ratios, increased percentages of pilot fuel result in increased efficiencies. However, at high over-all fuel-air ratios, the converse is true. These effects may be due to fuel staging as described in reference 5. It is believed that in this combustor these variations are at least in part due to (1) loss in efficiency because of maldistribution of vaporized fuel at low vaporizer flow rates, and (2) improvements in efficiency with increased percentages of vaporized fuel at conditions where the vaporized fuel is evenly distributed.

Maldistributed fuel was believed to be present when the vaporizer feed rates were low. Calculations based on the pressure at the capillary outlet (combustor-inlet pressure), the pressure drop across the capillaries, the probable temperature of the fuel in the manifold header, and the vapor pressure of the fuel (ref. 8) indicated that incipient boiling might occur in the header at flow rates below 28, 25, and 21 pounds per hour for test conditions A, B, and C, respectively. Such boiling would cause the capillaries leading from the upper side of the header to feed vapor fuel and those from the bottom to feed liquid fuel. Thus, an increase of pilot fuel flow at a given fuel-air ratio would mean an equivalent decrease in the amount of maldistributed fuel from the vaporizer and should be reflected in an increase in the combustion efficiency. The solid points and curves of figure 10 are used to indicate those data where vapor lock was probable. Conversely, the open points and broken lines indicate no vapor lock.

It is also apparent from figure 10, that for those conditions where header vapor lock does not occur, combustion efficiency increases with decreasing pilot fuel flow rates. This increase indicates a real gain in combustion efficiency resulting from prevaporized fuel injection. Such gains may be further illustrated by the data of figure 11, which compares the efficiency curves at condition B for optimized vapor-liquid injection and for atomized liquid injection alone. For the liquid system, the vaporizer was not used, and total fuel was supplied through a spray nozzle of a capacity sufficient to ensure favorable spray characteristics over a range of fuel flows at the single test condition. This nozzle ($7\frac{1}{2}$ gal/hr, 80° hollow cone) was operated at a pressure differential of 50 to 160 pounds per square inch for the data shown. It is apparent from figure 11 that for this combustor configuration, the use of vaporized fuel with atomizing pilot gave efficiencies about 30 percent greater than

using atomized fuel alone. However, since fuel atomization was not optimized over the entire range tested, the efficiencies for the liquid fuel injection system could be increased, especially at lower fuel flows, by improved atomization. However, at rich over-all fuel-air ratios where atomization was satisfactory, marked efficiency gains of the vapor-liquid system over the liquid fuel injection system were observed. Although combustion stability and generally high efficiency demand some pilot fuel supply, probably because of its action as a flame seat, piloting in excess of 15 to 25 percent of the total fuel generally resulted in lowered combustion efficiencies for these nonvapor-locking conditions.

Effect of combustor-inlet pressure and mass-flow rate. - Representative combustion efficiency data from table II are presented as functions of over-all fuel-air ratio in figure 12 for test conditions A to E. Data representing operation with poorly distributed vaporized fuel are shown by solid symbols, and open symbols are used where vaporizer feed rates were believed sufficient to yield even circumferential distribution of this fuel. The curves shown in figure 12 represent the efficiencies that can be obtained with optimized division of the fuel between pilot nozzle and vaporizer. Figures 12(a) to (c) show the performance obtained at combustor inlet pressures of 15, 8, and 6 inches of mercury at test conditions A, B, and C, respectively. Figures 12(d) and (e) show the performance obtained at test conditions D and E with a combustor-inlet pressure of approximately 15 inches of mercury absolute at air mass-flow rates 23 percent lower and 30 percent higher, respectively, than that used for test condition A. Combustor-inlet pressures for condition E varied from 15.3 to 17.3 inches of mercury absolute because of limitation of the test facility. These pressures are indicated in the figure. To facilitate the evaluation of the effect of combustor-inlet pressure and air mass-flow rate on combustion efficiency, the smoothed curves from figure 12 are replotted in figures 13 and 14. Combustor-inlet conditions, including reference velocity V_r, are listed in these figures. Reference velocity, as used therein, is based on the density of the air at combustor-inlet conditions and on the maximum cross-sectional area of the combustor.

Figure 13 shows the effect of combustor-inlet pressure on combustion efficiency. Reduction of the combustor-inlet pressure from 15 inches of mercury absolute to 8 and 6 inches of mercury absolute resulted in decreases in maximum efficiency from 95 to 88 and 82 percent, respectively. Also, combustion efficiency at the higher pressure was less affected by fuel-air ratio than were the lower pressure data.

Figure 14 shows the effect of changing air mass-flow rates on efficiency at near constant pressure. Combustion efficiencies are substantially the same for air mass-flow rates W_a/A of 2.78 and 2.14 pounds per second per square foot (test conditions A and D, respectively) over most of the fuel-air ratio range investigated; however, at

condition D, lean limit blow-out occurred at a fuel-air ratio of 0.0076, well above that for the higher air-flow condition. The efficiencies for the high air flow condition (3.62 lb/(sec)(sq ft) condition E) were substantially the same as for the other two conditions at fuel-air ratios above 0.014; at lower ratios the efficiencies were lower and the combustor reached its lean blow-out limit at about 0.011 fuel-air ratio. The data of figure 14 indicate that variations in air-flow rate over the range investigated had little effect on combustion efficiency except at lean conditions.

Data were obtained at condition F, which corresponds to a reference velocity of about 35 feet per second and should represent a mild combustion condition. However, the maximum efficiency obtained at this condition was only 93 percent. It appears that the final configuration of this combustor is efficiency-limited at around 93 to 95 percent. The 5-percent loss in efficiency may be the result of fuel losses from the vaporizer. Since the fit between the conical section of the primary and the secondary sleeve was not tight, a small quantity of liquid fuel might impinge in this area and leak through into the secondary dilution zone. Several light carbon streaks on the secondary sleeve in this region support this possibility. A second possibility is that liquid fuel impinging on the surface of the directional tubes was incompletely burned. Either or both are feasible sources of efficiency loss.

Comparison with a current production combustor. - Figure 15 is a replot of the curves from figure 12 of efficiency against temperature rise. Also shown are data from reference 9 for a current production tubular combustor of the same diameter operated at the same conditions. This figure indicates that higher efficiencies were obtained in the experimental combustor than in the production model at all test conditions. The greatest increases in efficiency were found at conditions of low inlet pressure. A further comparison between the efficiencies obtained with these two combustors is shown in figure 16 in terms of the correlating parameter V_r/P_iT_i proposed in reference 10. Comparisons are made at temperature-rise values of 680° and 1180° F, corresponding to 85 percent rated and full rated rotor speeds, respectively, in a 5.2-pressure-ratio engine. At a temperature rise of 680° F, the experimental combustor gave approximately 12 percent greater combustion efficiency than did the production combustor over the entire range of engine severities tested. At a temperature rise of 1180° F, the experimental combustor produced efficiencies greater than 75 percent at conditions much more severe than those resulting in blow-out in the production combustor.

Other Characteristics of Final Configuration

Combustor pressure drop. - A number of measurements of combustor pressure drop were made on the final configuration. The data are

presented in table III where test condition, temperature rise, pressure drop, and pressure drop coefficient are listed. The pressure drop coefficient $\Delta P/q$ (pressure drop across combustor/impact pressure at reference velocity conditions) of the final configuration had a value of approximately 18 for isothermal flow and increased to approximately 24 for 1100° F temperature rise. These pressure drop coefficients are equivalent to total-pressure-loss ratios $\Delta P/P_i$ of approximately 7 to 10 percent at a reference velocity of 100 feet per second.

Combustor-outlet temperature profile. - Combustor-outlet temperatures that were the averages of seven couples taken at centers of four annuli of equal areas as the couples traversed from near the wall to near the center of the duct were recorded. These average temperatures were fairly uniform, and the difference in temperature between the averages taken near the center of the duct and those taken near the wall was usually less than 200° F and never more than 400° F (fig. 6(d)). Circumferentially, however, the temperature profile at the combustor outlet was uneven. Figure 17 presents isotherms constructed from individual temperature readings taken at each of the 28 positions covered in the outlet-temperature instrumentation for test condition A at an average outlet temperature of 1475° F. A maximum difference in temperature of almost 700° F was present between the hottest and the coldest points. The lop-sided condition is the result of asymmetric inlet air flow, since a combustor rotation of 180° around its axis made practically no change in the location of the hot core of the outlet.

Carbon-deposition characteristics. - A single run was made to test the carbon-forming tendencies of the experimental combustor. For this run, the combustor was operated at 100 feet per second reference velocity and 60 inches of mercury absolute combustor-inlet pressure (test condition G) for 2 hours at an average outlet temperature of 1450° F. The fuel used was JP-4 (table I). No indication of carbon was found in the combustor at the end of this test.

Structural reliability. - The final combustor configuration was operated for approximately 100 hours during this investigation. The combustor exhibited no warping or burn-out of any of its components during this time. There was no evidence of fuel coking on the outer walls of the primary where the fuel was vaporized. Neither was there any tendency toward clogging in the capillary feed system, as shown by periodic testing of this system.

Flash-back limitations. - The most serious limitation in the range of operation of the experimental combustor was its tendency for flame either to flash back or to ignite spontaneously in the vaporization section of the combustor. Flash-back did not occur at any of the standard test conditions but was observed at low reference velocities, high combustor-inlet pressures, and especially at high heat-release rates. This condition may be one of flash-back through the stub tubes as a result of pressure pulses within the combustor. Test conditions F (inlet pressure P_i, 21 in. Hg; reference velocity V_r, 35 ft/sec) and G (inlet pressure P_i, 60 in. Hg; reference velocity V_r, 100 ft/sec) represent

the approximate limits at which the combustor could be operated without flash-back. Extended operation with flame burning in the vaporization region would certainly burn out the combustor. Therefore the combustor was watched closely during operation under conditions conducive to flash-back and was shut down immediately when this occurred. The limits imposed by flash-back would not permit the operation of this combustor at low altitudes in an actual engine, since at reference velocities of the order of 100 feet per second, combustor-inlet pressures could not exceed approximately 2 atmospheres.

CONCLUDING REMARKS

The combustor development work reported herein was the result of an attempt to convert to practice the design principle of approximately stoichiometric fuel-air admission. This design principle was not fully attained in two respects. First, it is believed that fuel vaporization was not complete for all fuel-flow rates and therefore a homogeneous fuel-air mixture was not charged to the primary zone. It is further believed that the design objectives of stoichiometric fuel-air admission were attained only at low over-all fuel-air ratios so that the primary zone probably operated at fuel-air ratios ranging from approximately stoichiometric at the lowest temperature-rise conditions to over three times rich of stoichiometric at the high-temperature rises. The combustor nevertheless is one which operated with incoming fuel-air mixtures which are believed to be much leaner than those of current prevaporizer practices.

Under simulated high-altitude conditions for 5.2-pressure-ratio engines (inlet pressures 15 and 8 in. Hg abs), the experimental prevaporizing combustor yielded efficiencies of 95 and 88 percent, which were as much as 20 percent higher than those obtained with a current production tubular combustor of the same diameter. These higher efficiencies were obtained in spite of the fact that the combustor was shorter by approximately 6 inches than the current production combustor. This reduced length resulted from the installation of the primary airflow control mechanism during the initial development stages. This control was not used in the later stages of testing and could have been omitted to make available increased combustion volume.

The combustor also represented a minimum of the cut-and-try empirical design characteristic to the development of a successful combustor. Considerable time was spent on the development of the secondary sleeve and in the initial development of the primary liner, but the stub tube configuration shown in the final burner was the only one tested. Additional gains in performance might result from a systematic study of primary zone variations.

The design principle yielded a burner which had the objectionable quality of flashing back at mild conditions. It is not known whether this flash-back was pressure-induced propagation up the stub tubes or

whether it was due to spontaneous ignition from hot metal surfaces in the vaporizer area. The former situation might be corrected by inserting screens in the stub tubes and the latter by control of the vaporizer metal temperatures through insulation. In any case, a cure for flash-back would have to be found before this type combustor could be seriously considered as an engine component. Together with the satisfactory altitude efficiencies, there are indications that the combustor reliability is satisfactory. In particular, the design principle might result in a combustor with exceptional freedom from coking. In a single test at above-atmospheric conditions, the burner showed no trace of deposits. The fact that only blue flames were observed at 60-inch mercury pressure and a fuel-air ratio of 0.02 suggests that the carbon-forming tendencies of this burner would be very low.

In general, it has been demonstrated that the design principle of near-stoichiometric fuel-air admission is practicable and may result in a combustor which is efficient and carbon-free, even under severe operating conditions.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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TABLE I. - FUEL ANALYSIS

Properties	MIL-F-5624B grade JP-4
Distillation A.S.T.M. D-86, °F	
Initial boiling point	139
Percentage evaporated	
10	253
20	291
30	311
40	324
50	333
60	347
70	363
80	382
90	413
Final boiling point	486
Residue, percent	1.2
Loss, percent	.7
Aromatics, percent by volume silica gel	10
Reid vapor pressure, lb/sq in.	2.7
Specific gravity, 60° F	.776
Hydrogen-carbon ratio	.168
Aniline point, °F	137
Lower heat of combustion, Btu/lb	18,675
Smoke point, mm	32

TABLE II. - EXPERIMENTAL DATA FOR $9\frac{1}{2}$-INCH TUBULAR COMBUSTOR

Combustor inlet		Air flow		Fuel-flow rate, lb/hr			Fuel to pilot, percent	Vapor fuel pressure, in. Hg abs	Fuel-air ratio, F/A	Outlet temperature, T_0, °F	Temperature rise, ΔT, °F	Combustion efficiency, η_b, percent
Pressure, P_1, in. Hg abs	Temperature, T_1, °F	lb/sec	lb/(sec)(sq ft)	Pilot	Vaporizer	Total						
Test condition A; vaporizer with pilot												
15.0	250	1.375	2.789	15.9	13.9	29.8	53	29	0.0060	----	----	(a)
	250	1.375	2.789	15.9	17.8	33.7	47	32	.0068	631	381	75
	250	1.375	2.789	15.9	23.7	39.6	40	38	.0080	716	466	79
	250	1.380	2.795	9.7	35.7	45.4	21	50	.0091	----	----	(a)
	250	1.375	2.789	15.9	29.7	45.6	35	44	.0092	841	591	88
	250	1.380	2.795	16.9	29.7	46.6	36	44	.0094	864	614	90
	250	1.380	2.795	9.7	41.5	51.2	19	56	.0103	----	----	(a)
	250	1.375	2.789	15.9	35.7	51.6	31	50	.0104	944	694	92
	250	1.380	2.795	9.7	45.5	55.2	18	60	.0111	995	745	93
	250	1.375	2.789	15.9	41.5	57.4	28	56	.0116	1038	788	95
	250	1.375	2.789	15.9	47.4	63.3	25	61	.0128	1110	860	94
	250	1.380	2.795	15.9	55.2	71.1	22	69	.0143	1204	954	94
	250	1.370	2.775	9.7	65.1	74.8	13	79	.0152	1240	990	93
	250	1.380	2.795	15.9	65.1	81.0	20	79	.0163	1294	1044	92
	250	1.380	2.795	15.9	75.1	91.0	17	89	.0183	1396	1146	90
	250	1.380	2.795	15.9	85.0	100.9	16	98	.0203	1493	1243	90
	255	1.370	2.775	15.9	85.0	100.9	16	98	.0203	1500	1245	89
Test condition B; vaporizer with pilot												
8.0	230	0.730	1.481	19.1	0.7	19.8	97	9	0.0075	718	488	88
	230	.730	1.481	19.6	.2	19.8	99	8	.0075	722	492	88
	230	.730	1.481	15.2	4.6	19.8	77	13	.0075	----	----	(a)
	230	.730	1.481	13.8	6.0	19.8	70	14	.0075	----	----	(a)
	215	.739	1.500	13.5	12.3	25.8	52	20	.0097	798	583	82
	230	.730	1.481	16.8	9.0	25.8	65	17	.0098	830	600	84
	230	.730	1.481	22.2	3.6	25.8	86	11	.0098	854	624	87
	230	.730	1.481	24.3	1.5	25.8	94	9	.0098	856	626	87
	220	.737	1.495	11.1	16.9	28.0	40	25	.0111	864	644	84
	215	.737	1.495	14.9	14.9	29.8	50	23	.0112	895	680	83
	230	.730	1.481	25.1	4.7	29.8	84	13	.0113	929	699	85
	225	.729	1.479	10.3	19.5	29.8	34	26	.0114	----	----	(a)
	220	.737	1.495	13.7	14.8	28.5	48	23	.0115	884	664	85
	220	.737	1.495	13.7	17.3	31.0	44	25	.0117	929	709	84
	220	.737	1.495	13.7	17.2	30.9	44	25	.0117	944	724	86
	220	.730	1.481	11.7	22.0	33.7	35	30	.0128	1000	780	85
	230	.730	1.481	22.0	11.7	33.7	65	20	.0128	1004	774	84
	215	.728	1.478	16.3	17.4	33.7	48	25	.0129	980	765	83
	225	.724	1.470	10.3	23.4	33.7	30	31	.0129	1019	794	85
	225	.722	1.466	8.6	25.1	33.7	25	33	.0129	1028	803	87
	225	.724	1.470	----	33.7	33.7	--	41	.0129	----	----	(a)
	210	.740	1.500	13.6	23.1	36.7	37	29	.0138	1063	853	86
	225	.735	1.490	8.4	28.4	36.8	23	36	.0139	1090	865	87
	225	.735	1.490	13.7	23.2	36.9	37	31	.0140	1073	848	85
	215	.742	1.505	18.7	20.9	39.6	47	29	.0148	1096	876	83
	220	.728	1.478	13.6	26.0	39.6	34	34	.0149	1130	910	85
	225	.730	1.481	11.8	27.8	39.6	30	35	.0149	1134	909	85
	225	.722	1.466	9.7	29.9	39.6	24	37	.0149	1144	919	85
	225	.727	1.475	7.9	31.7	39.6	20	39	.0149	1149	924	86
	230	.731	1.483	25.9	13.7	39.6	66	21	.0149	1106	876	82
	230	.726	1.475	----	39.6	39.6	--	43	.0152	----	----	(a)
	210	.740	1.500	13.6	27.1	40.7	34	35	.0153	1145	935	86
	215	.735	1.490	13.6	31.0	44.6	30	38	.0169	1214	999	84
	220	.740	1.500	21.5	24.0	45.5	47	32	.0171	1200	980	82
	220	.729	1.480	16.4	29.1	45.5	36	37	.0173	1234	1014	84
	225	.730	1.481	13.3	32.2	45.5	29	40	.0173	1222	997	82
	225	.724	1.470	10.5	35.0	45.5	23	42	.0174	1244	1019	83
	225	.727	1.475	8.6	36.9	45.5	19	44	.0174	1260	1035	85
	225	.726	1.473	----	45.5	45.5	--	53	.0174	1220	990	81
	215	.730	1.481	13.6	35.0	48.6	28	42	.0185	1215	1000	77
	225	.732	1.485	13.7	35.1	48.8	28	42	.0185	1308	1083	84
8.1	225	.742	1.505	----	51.4	51.4	--	58	.0193	1315	990	80
8.0	225	.730	1.481	----	51.4	51.4	--	58	.0195	1203	978	72
	215	.735	1.490	13.6	39.0	52.6	26	46	.0199	1288	1073	78
	225	.732	1.485	8.4	44.2	52.6	26	51	.0200	1305	1080	78

[a]Blow-out.

TABLE II. - Continued. EXPERIMENTAL DATA FOR $9\frac{1}{2}$-INCH TUBULAR COMBUSTOR

Combustor inlet		Air flow		Fuel-flow rate, lb/hr			Fuel to pilot, percent	Vapor fuel pressure, in. Hg abs	Fuel-air ratio, F/A	Outlet temperature, T_0, °F	Temperature rise, ΔT, °F	Combustion efficiency, η_b, percent
Pressure, P_1, in. Hg abs	Temperature, T_1, °F	lb/sec	lb/(sec)(sq ft)	Pilot	Vaporizer	Total						
Test condition B; vaporizer with pilot - concluded												
8.0	220	0.735	1.490	25.2	30.0	55.2	46	37	0.0208	1246	1026	71
	225	.729	1.480	15.8	39.4	55.2	29	47	.0210	1366	1141	79
	225	.727	1.475	10.1	45.1	55.2	18	52	.0211	1405	1180	82
	220	.740	1.500	13.6	42.6	56.2	24	50	.0211	1358	1138	78
	225	.730	1.481	13.5	42.3	55.8	15	49	.0212	1379	1154	79
	225	.724	1.468	12.7	42.5	55.2	23	50	.0212	1350	1125	77
	220	.720	1.462	18.3	36.9	55.2	33	44	.0213	1332	1112	76
	225	.718	1.458	----	55.2	55.2	--	62	.0213	1400	1170	81
	225	.730	1.481	13.4	44.4	57.8	23	51	.0220	1424	1199	80
8.2	225	.742	1.505	13.7	46.5	60.2	23	64	.0227	1415	1190	77
8.0	220	.735	1.490	13.5	46.9	60.4	22	64	.0228	1415	1195	77
8.0	225	.728	1.478	13.4	47.2	60.6	22	64	.0231	1471	1246	79
8.1	225	.738	1.481	----	62.0	62.0	--	69	.0236	1496	1271	77
8.1	225	.742	1.505	13.7	49.9	63.6	21	57	.0238	1451	1226	75
8.0	220	.730	1.481	13.5	49.0	62.5	22	56	.0238	1429	1209	74
	225	.728	1.478	13.4	49.6	63.0	21	57	.0241	----	----	(a)
	210	.740	1.500	13.5	50.9	64.4	21	58	.0245	----	----	(a)
Test condition B; pilot fuel only												
8.0	210	0.740	1.500	31.0	----	31.0	100	--	0.0116	695	485	57
	210	.740	1.500	42.2	----	42.2	100	--	.0158	849	639	56
	210	.740	1.500	47.8	----	47.8	100	--	.0179	915	705	55
	210	.740	1.500	57.2	----	57.2	100	--	.0218	1032	822	54
Test condition C; vaporizer with pilot												
6.0	220	0.455	0.922	13.8	----	13.8	100	--	0.0084	718	498	80
	210	.457	.924	9.1	4.7	13.8	65	11	.0084	----	----	(a)
	210	.457	.924	12.0	1.8	13.8	87	8	.0084	----	----	(a)
	210	.450	.912	6.6	8.1	14.7	45	14	.0090	----	----	(a)
	210	.450	.912	7.2	8.1	15.3	47	14	.0094	759	549	79
	210	.460	.932	8.4	9.0	17.4	48	15	.0105	814	604	78
	210	.466	.944	14.6	3.2	17.8	82	9	.0106	831	621	80
	205	.450	.912	----	17.2	17.2	---	23	.0106	836	631	80
	220	.463	.938	17.8	----	17.8	100	--	.0107	825	605	78
	210	.465	.942	9.8	8.4	18.2	54	14	.0109	864	654	83
	210	.465	.942	9.8	8.4	18.2	54	14	.0109	861	651	82
	210	.465	.942	5.9	13.2	19.1	31	19	.0114	880	670	81
	210	.463	.938	5.9	13.2	19.1	31	19	.0114	885	675	82
	205	.465	.942	4.9	14.0	18.9	26	20	.0114	----	----	(a)
	210	.459	.930	11.5	7.7	19.2	60	14	.0116	----	----	(a)
	210	.465	.942	7.1	12.4	19.5	36	18	.0116	905	695	82
	210	.465	.942	11.1	8.6	19.7	56	14	.0118	904	694	81
	210	.463	.938	11.1	8.6	19.7	56	14	.0118	935	725	85
	205	.465	.942	5.9	14.2	20.1	29	20	.0120	924	719	82
	210	.466	.944	17.6	4.2	21.8	81	10	.0130	955	745	80
	215	.463	.938	21.8	----	21.8	100	--	.0131	988	773	82
	210	.455	.922	7.2	14.4	21.6	70	20	.0132	993	783	82
	210	.460	.932	9.8	12.4	22.4	44	18	.0135	1009	799	82
	210	.457	.924	13.5	8.3	21.8	62	14	.0132	959	749	79
	210	.457	.924	11.5	10.3	21.8	53	16	.0132	971	761	80
	210	.459	.930	9.8	12.0	21.8	45	18	.0132	955	745	78
	210	.459	.930	8.8	14.4	21.8	38	20	.0140	----	----	(a)
	210	.465	.942	10.2	14.7	24.9	41	20	.0149	1083	873	82
	210	.464	.940	15.5	10.3	25.8	60	16	.0154	1105	895	82
	210	.459	.930	11.3	14.5	25.8	44	20	.0154	1094	884	80
	210	.459	.930	8.1	17.7	25.8	31	23	.0154	1114	904	81
	210	.463	.938	12.8	13.0	25.8	50	19	.0155	1094	884	81
	210	.463	.938	20.2	5.6	25.8	78	11	.0155	1094	884	80
	210	.457	.924	25.8	----	25.8	100	--	.0157	908	698	62
	205	.465	.942	5.9	20.7	26.6	24	26	.0159	1118	913	81
	210	.455	.922	13.6	13.1	26.7	51	19	.0163	1116	906	78
	205	.460	.932	13.8	15.3	29.1	48	21	.0176	1173	968	78
	210	.466	.944	22.8	7.0	29.8	77	13	.0178	1066	856	68
	205	.460	.932	7.2	22.3	29.8	24	28	.0178	1196	991	79
	210	.460	.932	5.9	24.1	30.0	20	30	.0181	1224	1014	80

[a]Blow-out.

TABLE II. - Concluded. EXPERIMENTAL DATA FOR $9\frac{1}{2}$-INCH TUBULAR COMBUSTOR

Combustor inlet		Air flow		Fuel-flow rate, lb/hr			Fuel to pilot, percent	Vapor fuel pressure, in. Hg abs	Fuel-air ratio, F/A	Outlet temperature, T_0, °F	Temperature rise, ΔT, °F	Combustion efficiency, η_b, percent
Pressure, P_1, in. Hg abs	Temperature, T_1, °F	lb/sec	lb/(sec)(sq ft)	Pilot	Vaporizer	Total						
Test condition C; vaporizer with pilot - concluded												
6.0	210	0.460	0.932	5.9	24.1	30.0	20	30	0.0181	1235	1025	81
	210	.460	.932	8.4	22.5	30.9	27	28	.0186	1103	893	68
	205	.470	.952	5.9	26.3	32.2	34	32	.0180	1258	1053	79
	205	.460	.932	9.8	22.6	32.4	32	28	.0197	1190	985	72
	210	.460	.932	13.7	19.3	33.0	41	25	.0199	1145	935	67
	205	.460	.932	7.2	26.3	33.5	22	32	.0202	1209	1004	71
	210	.459	.930	25.4	8.3	33.7	76	14	.0204	1108	898	63
	210	.466	.944	13.8	19.9	33.7	41	25	.0204	1241	1031	74
	210	.459	.930	9.5	24.2	33.7	28	30	.0204	1312	1102	78
	210	.459	.930	----	33.7	33.7	--	39	.0204	1329	1119	79
	210	.455	.922	19.2	14.5	33.7	57	20	.0206	1180	975	68
	210	.463	.938	16.2	17.5	33.7	48	23	.0210	1179	969	69
	205	.455	.922	9.8	26.6	36.4	25	32	.0222	1261	1056	69
	205	.465	.942	9.8	24.5	34.3	29	30	.0223	----	----	(a)
	205	.460	.932	7.2	30.2	37.4	19	36	.0226	1315	1110	71
	205	.455	.922	13.8	23.2	37.0	37	29	.0226	1270	1065	68
	210	.459	.930	21.2	16.5	37.7	56	22	.0228	1236	1026	65
	205	.465	.942	5.9	32.4	38.3	15	38	.0229	1340	1135	72
	210	.463	.938	8.4	30.4	38.8	22	36	.0233	1407	1197	75
	210	.464	.940	----	39.6	39.6	--	45	.0237	1424	1214	75
	210	.459	.930	10.5	29.1	39.6	27	34	.0239	1384	1174	72
	205	.465	.942	9.8	30.5	40.3	24	36	.0241	1353	1148	70
	210	.460	.932	11.1	28.8	39.9	28	34	.0241	1361	1151	70
	210	.460	.932	13.7	26.6	40.3	34	32	.0243	1361	1151	69
	205	.465	.942	13.8	27.2	41.0	34	33	.0245	1328	1123	67
	205	.465	.942	7.2	34.1	41.3	17	39	.0246	1389	1184	70
	210	.459	.930	22.1	19.2	41.3	54	25	.0250	----	----	(a)
	210	.460	.932	13.7	28.2	41.9	33	34	.0253	----	----	(a)
	210	.460	.932	11.1	30.7	41.8	26	36	.0253	1413	1203	70
	205	.455	.922	5.9	36.0	41.9	14	41	.0256	1390	1185	68
	210	.463	.938	19.4	23.4	42.8	45	29	.0257	----	----	(a)
	210	.466	.944	16.6	26.6	43.2	39	32	.0257	----	----	(a)
	210	.459	.930	11.3	31.9	43.2	26	37	.0262	----	----	(a)
	205	.460	.932	7.2	36.1	43.3	17	41	.0262	1406	1201	68
	205	.465	.842	5.9	38.0	43.9	17	43	.0262	1411	1206	68
	210	.460	.932	11.1	32.7	43.8	25	38	.0264	----	----	(a)
	205	.465	.942	13.7	31.0	44.8	22	50	.0267	----	----	(a)
Test condition D; vaporizer with pilot												
15.0	245	1.035	2.100	15.3	17.8	33.1	46	32	0.0089	864	619	95
	245	1.055	2.140	15.9	21.8	37.7	42	36	.0099	928	683	95
	245	1.060	2.148	15.9	25.8	41.7	38	40	.0109	995	750	95
	245	1.035	2.100	15.9	30.8	46.7	35	45	.0125	1079	834	93
	240	1.060	2.148	15.9	35.8	51.7	31	50	.0136	1153	913	95
	240	1.060	2.148	15.9	40.5	56.4	28	55	.0148	1220	980	94
	240	1.060	2.148	15.9	45.5	61.4	26	60	.0161	1283	1043	93
	240	1.065	2.158	15.9	50.4	66.3	24	64	.0173	1369	1129	94
	240	1.065	2.158	15.9	55.2	71.1	22	69	.0186	1423	1183	92
	240	1.065	2.158	15.9	60.2	76.1	21	74	.0199	1478	1238	91
Test condition E; vaporizer with pilot												
15.3	255	1.770	3.590	15.9	55.8	71.7	22	70	0.0112	----	----	(a)
15.4	255	1.760	3.570	15.9	55.2	71.1	22	70	.0112	975	720	89
15.6	255	1.760	3.570	15.9	57.2	73.1	22	72	.0115	1013	758	91
15.7	255	1.765	3.580	15.9	60.2	76.1	21	75	.0120	1049	794	92
15.7	255	1.770	3.590	15.9	65.1	81.0	20	80	.0127	1086	831	92
16.1	255	1.765	3.580	15.9	70.2	86.1	18	85	.0135	1150	895	93
16.1	255	1.770	3.590	15.9	75.2	91.1	17	90	.0143	1184	929	92
16.4	255	1.765	3.580	15.9	80.0	95.9	17	95	.0151	1248	993	94
16.5	255	1.775	3.600	15.9	85.0	100.9	15	100	.0156	1276	1021	93
16.6	255	1.765	3.580	15.9	89.8	105.7	15	105	.0166	1329	1074	93
16.7	255	1.775	3.600	15.9	94.7	110.6	14	109	.0173	1363	1108	92
16.9	255	1.770	3.590	15.9	99.4	115.3	14	114	.0181	1409	1154	92
17.0	255	1.770	3.590	15.9	103.8	119.7	13	119	.0188	1439	1184	92
17.2	255	1.770	3.590	15.9	109.1	125.0	13	124	.0196	1484	1229	92
17.3	255	1.770	3.590	15.9	112.5	128.4	12	127	.0201	1513	1258	92
Test condition F; vaporizer with pilot												
21.0	220	0.74	1.497	13.6	8.9	22.5	40	30	0.0084	798	578	93
21.0	220	.73	1.478	13.6	13.1	26.7	51	34	.0101	909	689	93
22.0	220	.74	1.497	13.6	21.2	34.8	39	43	.0131	1079	859	92
22.0	220	.74	1.497	13.6	29.2	42.8	32	51	.0161	1251	1031	91
22.0	220	.73	1.478	13.6	37.1	50.7	27	58	.0193	1406	1186	89

[a]Blow-out.

TABLE III. - PRESSURE DROP CHARACTERISTICS OF

EXPERIMENTAL COMBUSTOR

Test condition	Inlet pressure, in. Hg abs	Temperature rise, $^{\circ}F$	Pressure drop, ΔP, in. H_2O	Pressure drop coefficient, $\Delta P/q$
A	15.0	---	13.5	16.3
A	15.0	466	17.0	20.5
A	15.0	591	18.0	21.7
A	15.0	788	18.5	22.3
A	15.0	1146	19.5	23.5
A	15.2	1275	20.0	24.1
B	8.0	----	8.2	18.6
B	8.0	----	7.75	17.6
B	10.0	795	8.5	19.3
B	8.0	822	8.5	19.3
B	8.0	853	9.5	21.5
B	8.0	865	10.0	22.7
B	8.0	1083	10.0	22.7
D	15.0	834	10.0	16.1
E	15.0	---	25.0	17.1
E	15.7	831	29.0	19.8
E	16.5	1021	29.5	20.2

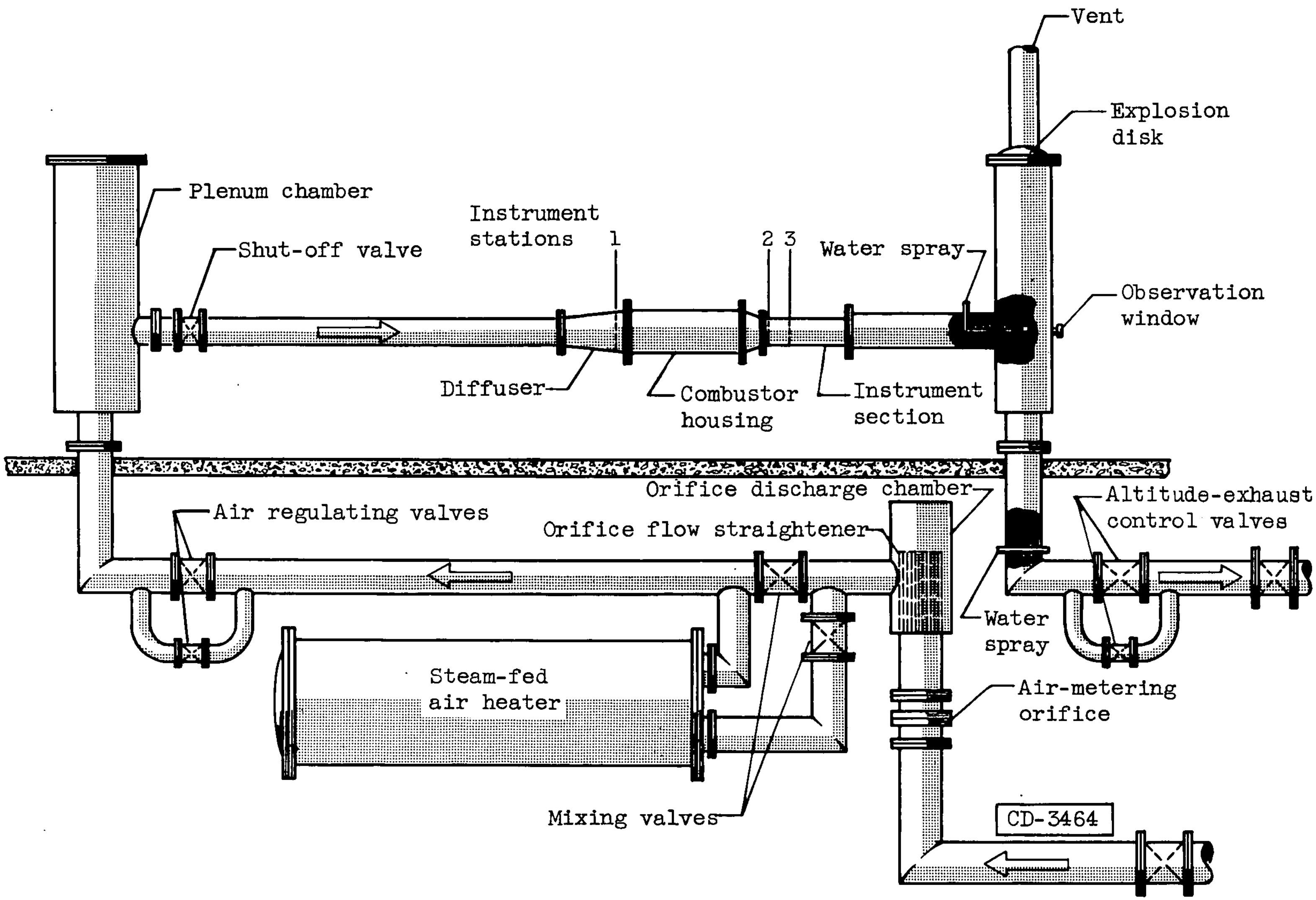
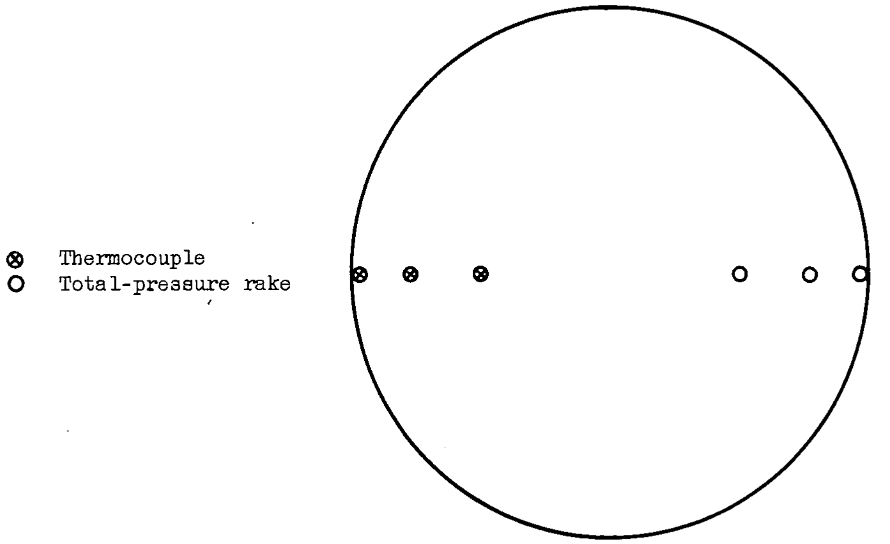
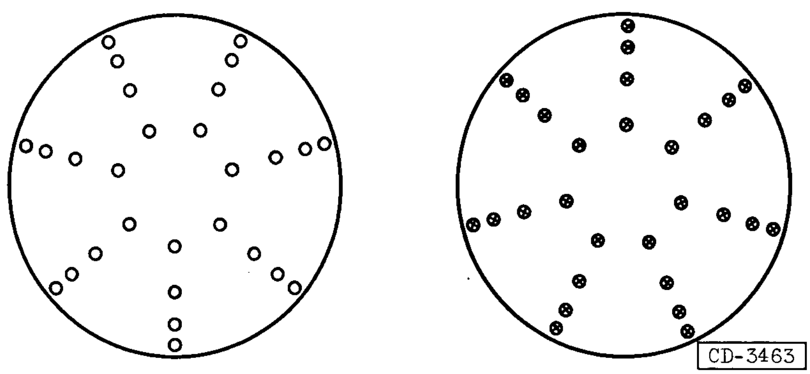


Figure 1. - Installation of $9\frac{1}{2}$-inch-diameter experimental tubular combustor.



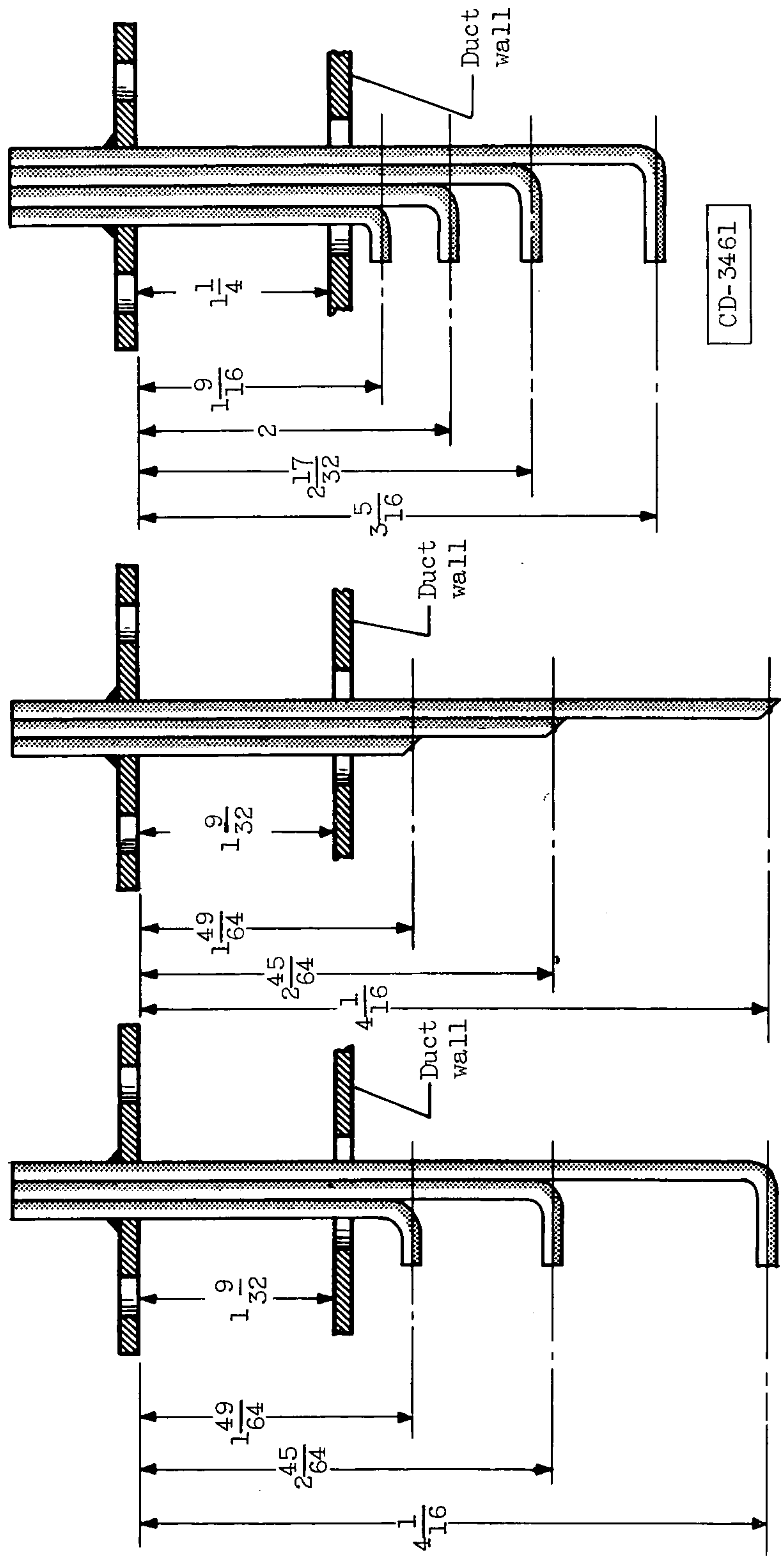
(a) Inlet thermocouples (chromel-alumel) and inlet total-pressure rake at station 1.



(b) Outlet total-pressure rakes in plane at station 2.

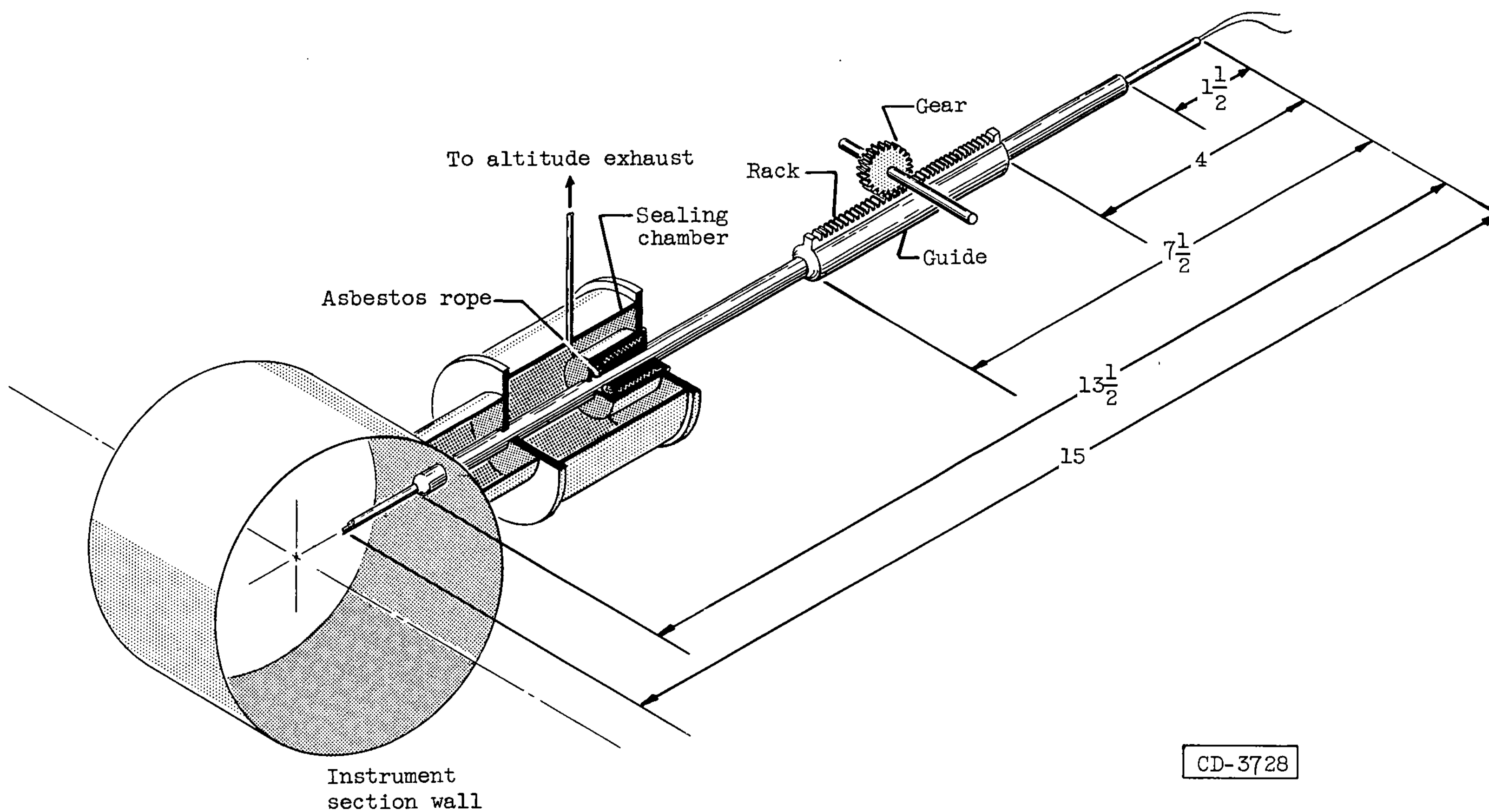
(c) Temperature-recording positions of seven movable outlet thermocouples (chromel-alumel) in plane at station 3.

Figure 2. - Pressure and temperature instrumentation of experimental combustor.



(a) Inlet total-pressure rake. (b) Inlet thermocouple. (c) Outlet total-pressure rake.

Figure 3. - Combustor instrumentation. (Dimensions are in inches.)



(d) Movable outlet thermocouple.

Figure 3. - Concluded. Combustor instrumentation. (Dimensions are in inches.)

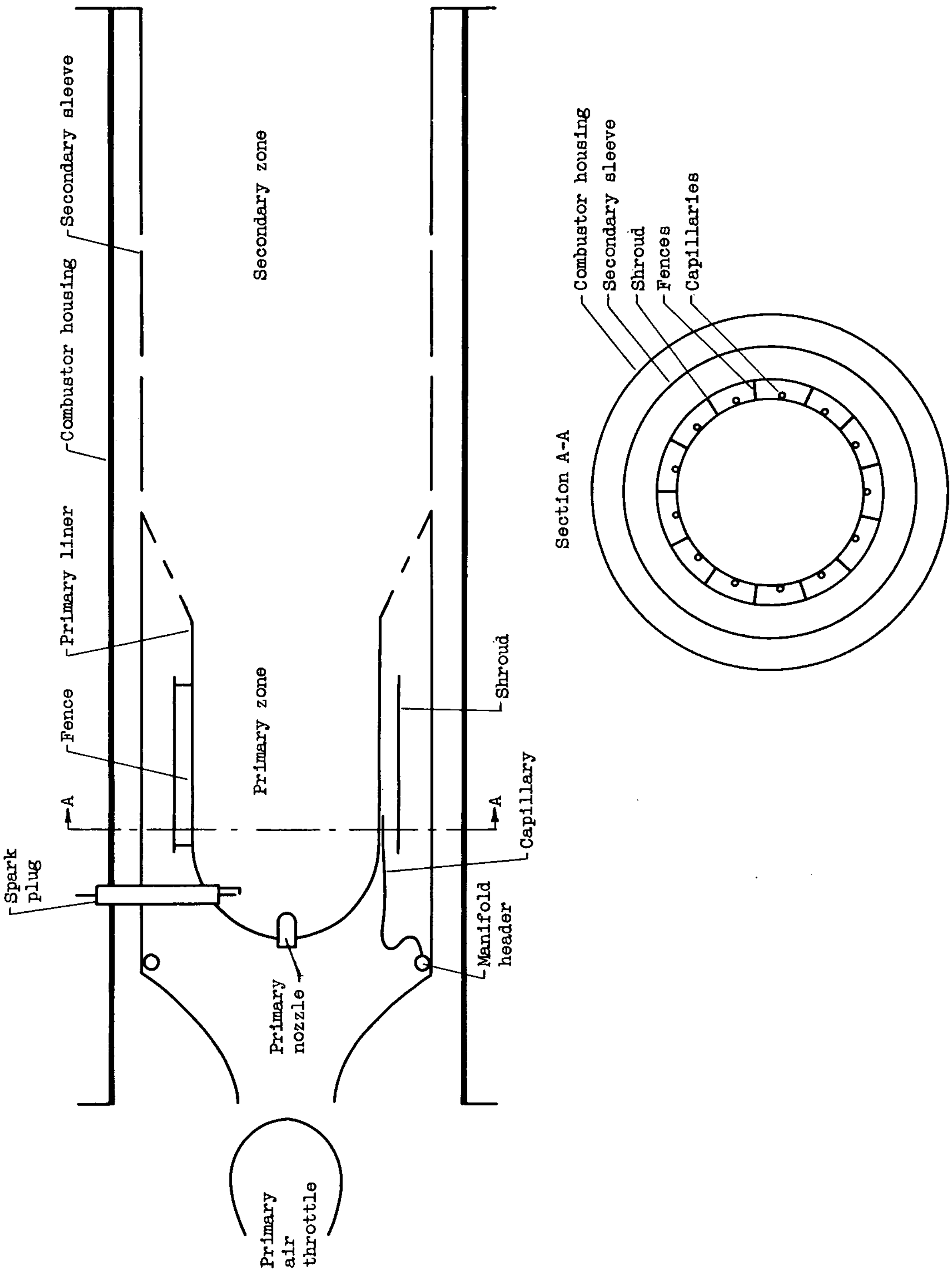
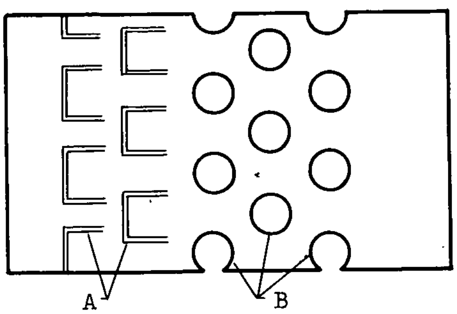


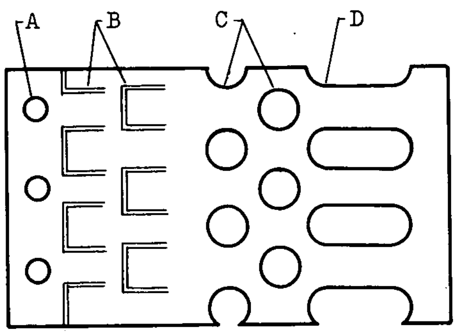
Figure 4. - General design and component orientation of experimental combustor.



A Louvers: 1" by 1", raised 1/4"; 2 rings, 13 per ring

B Holes: 1"; 3 rings, 13 per ring

(a) Configuration M-1.



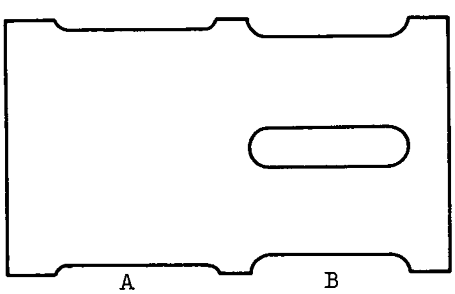
A 13 Holes: 5/8"

B Louvers: 1" by 1", raised 1/4"; 2 rings, 13 per ring

C Holes: 1"; 2 rings, 13 per ring

D 13 Slots: 1" by $2\frac{1}{2}$"

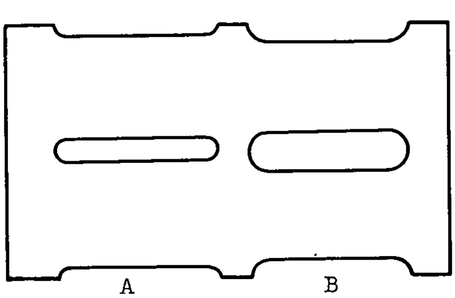
(b) Configuration M-2.



A 4 Slots: 1/2" by 4"

B 8 Slots: 1" by 4"

(c) Configuration M-3.

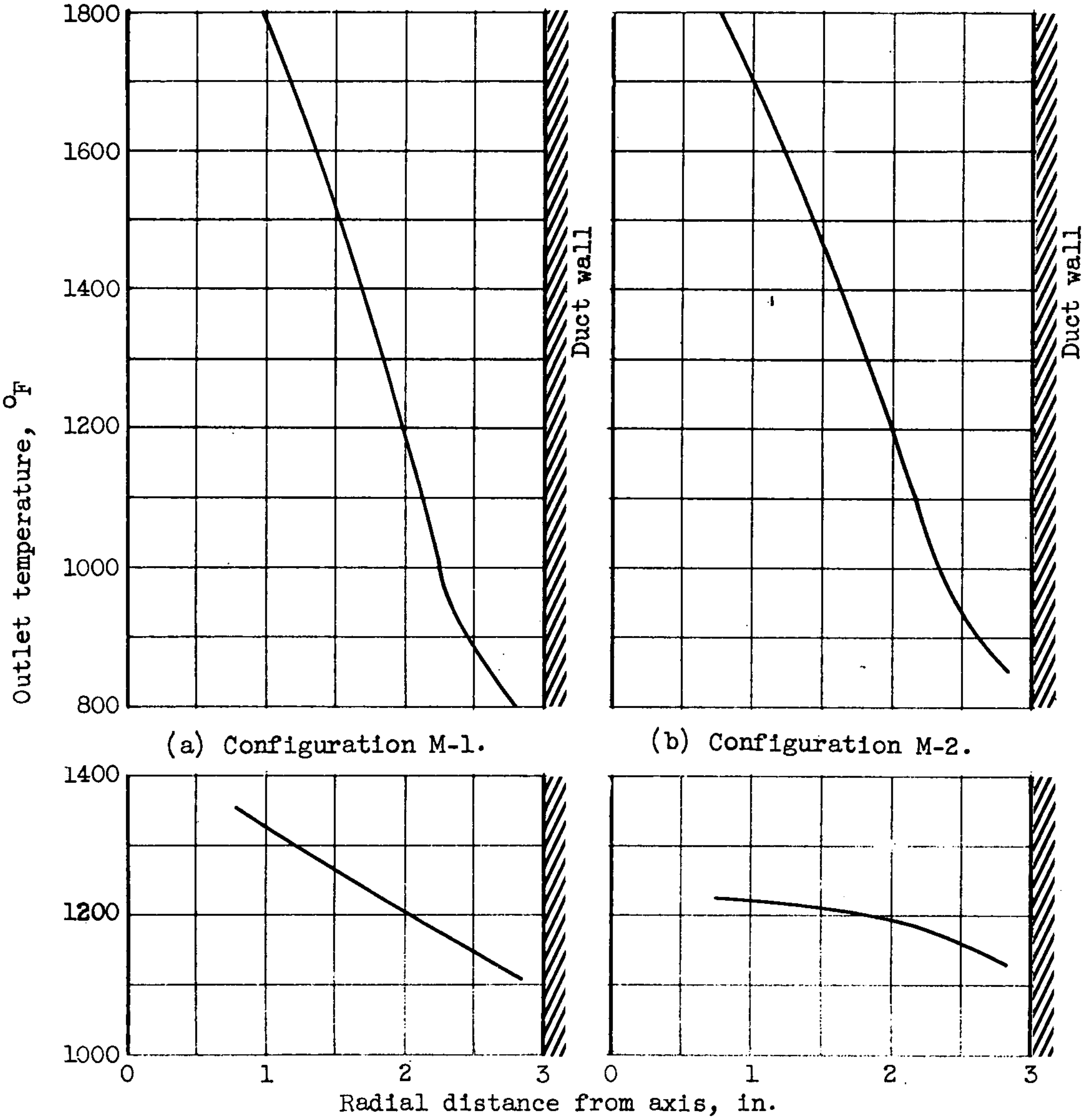


A 8 Slots: 3/8" by 4"

B 8 Slots: 1" by 4"

(d) Configuration M-4.

Figure 5. - Experimental secondary sleeves showing hole configurations; quarter sections.



(c) Configuration M-3. (d) Configuration M-4.

Figure 6. - Outlet temperature profiles obtained with four different secondary sleeve configurations.

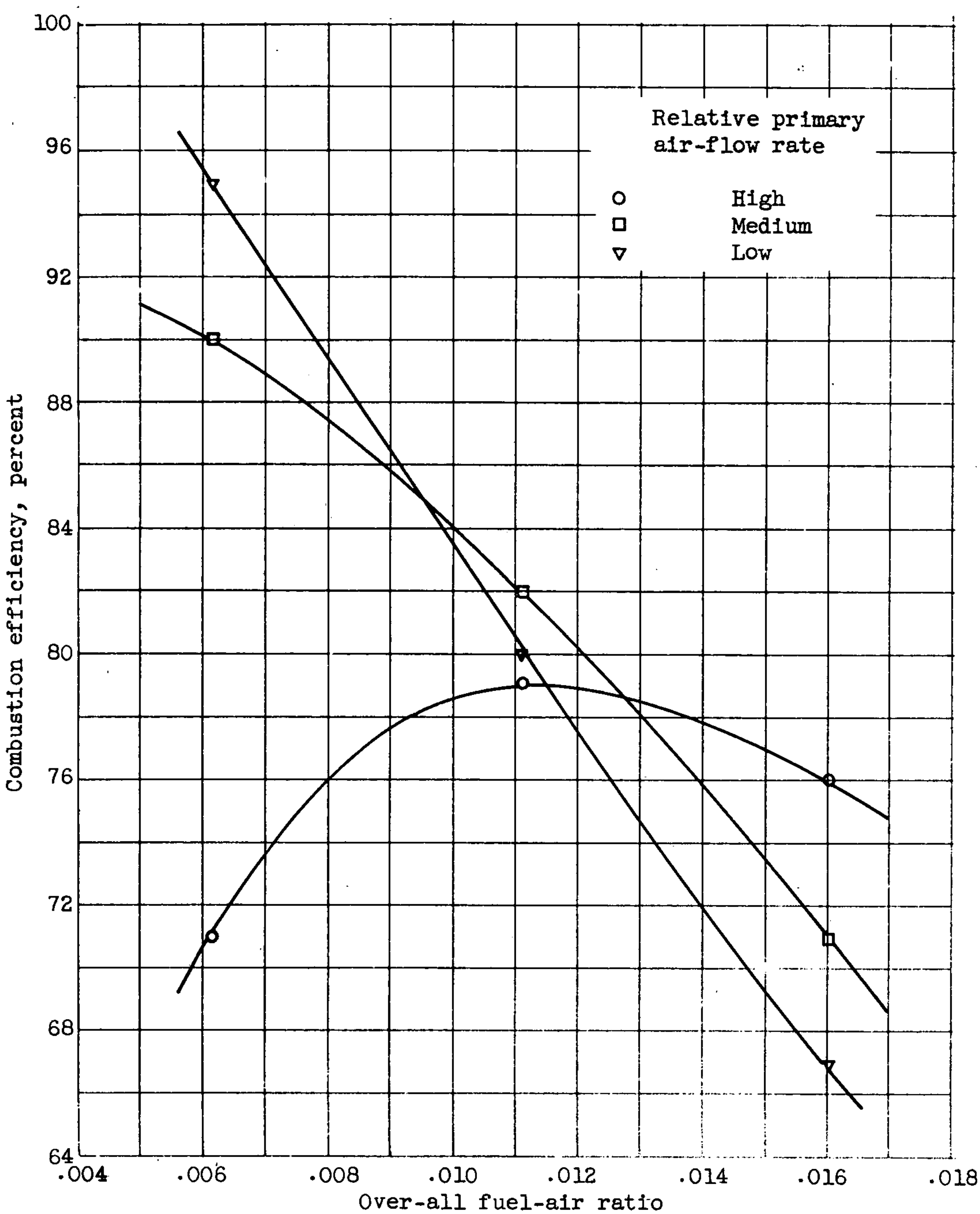


Figure 7. - Effect of relative primary air flow on combustion efficiency. Test condition A: inlet pressure P_1, 15 inches of mercury absolute; inlet temperature T_1, 250° F; air flow W_a/A, 2.78 pounds per second per square foot.

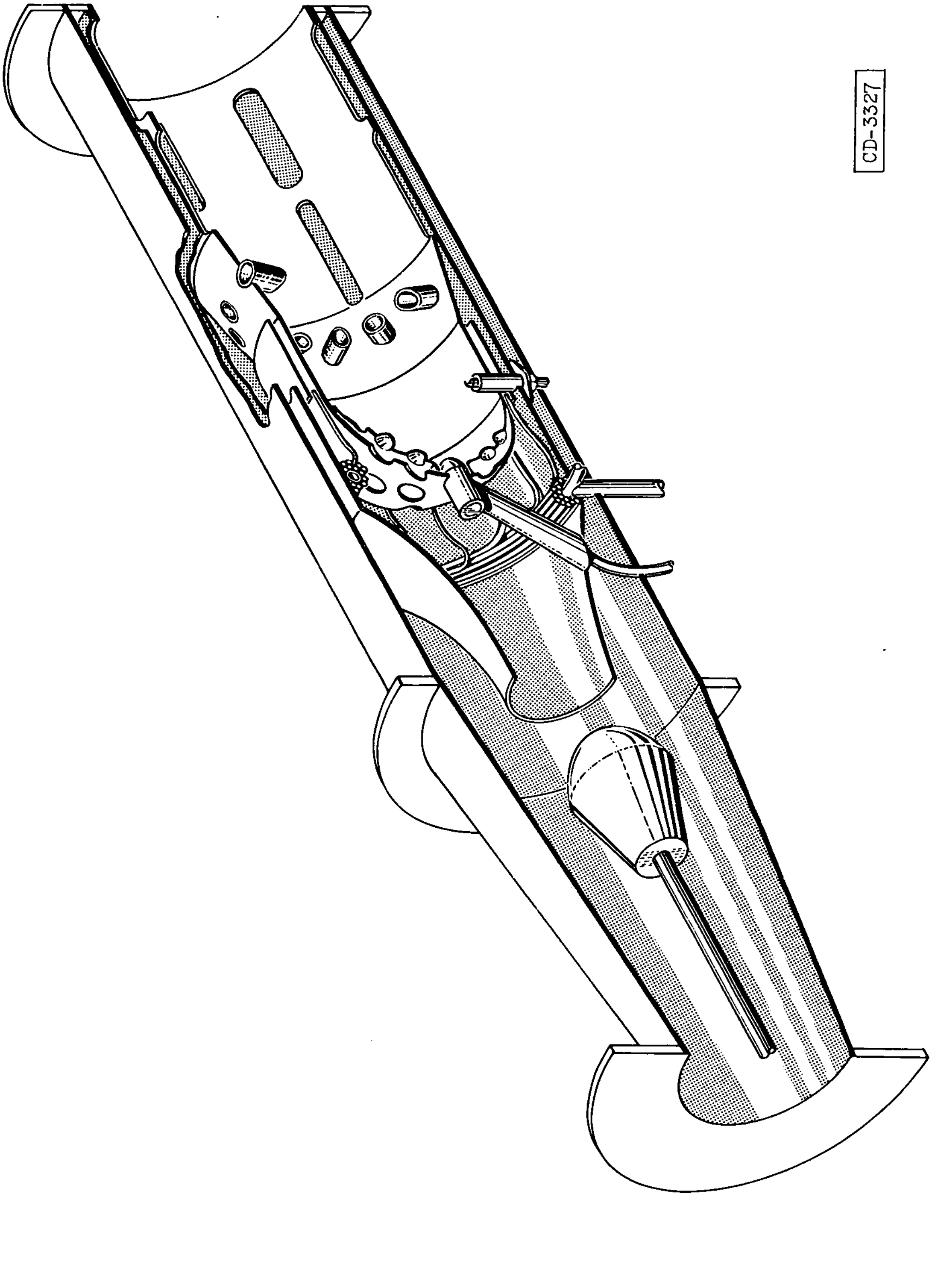
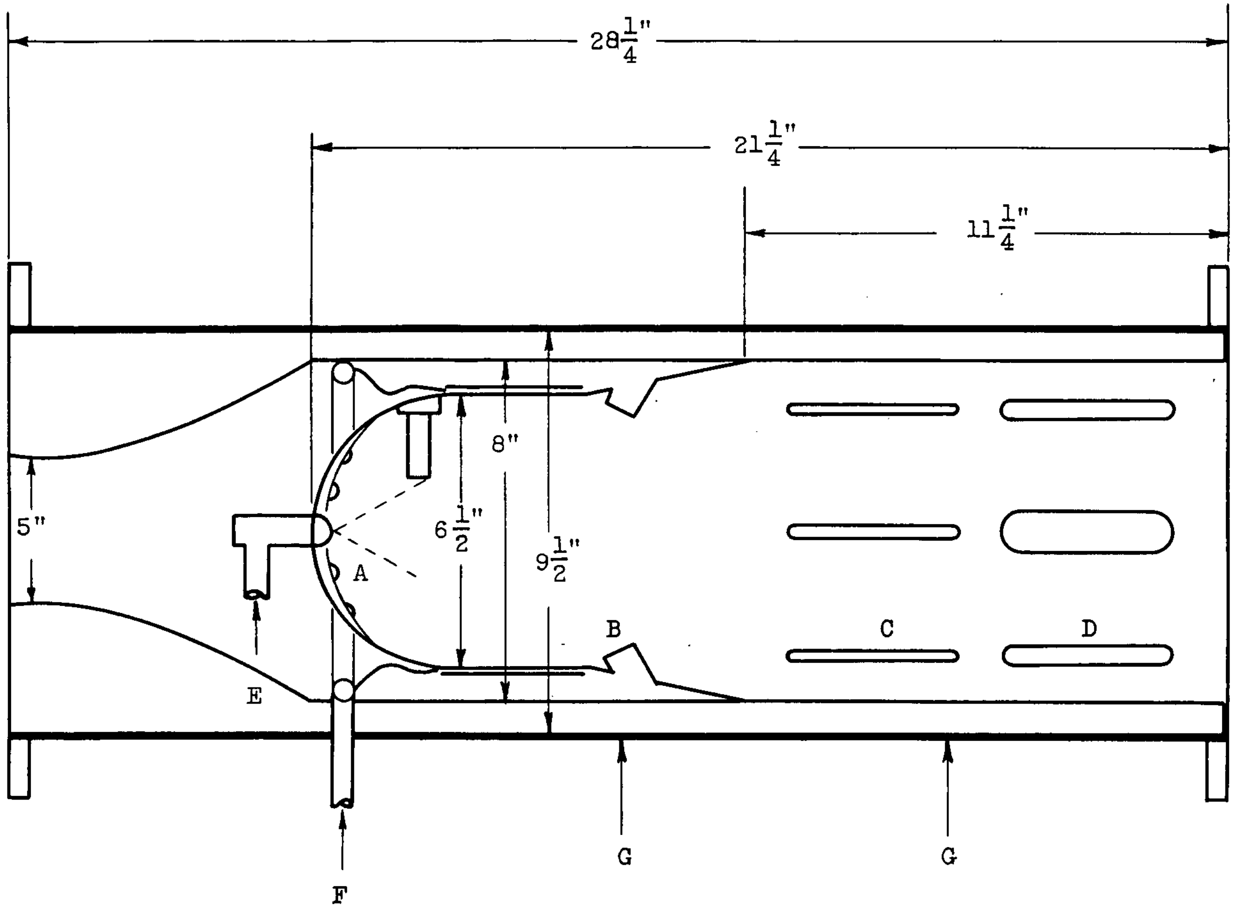
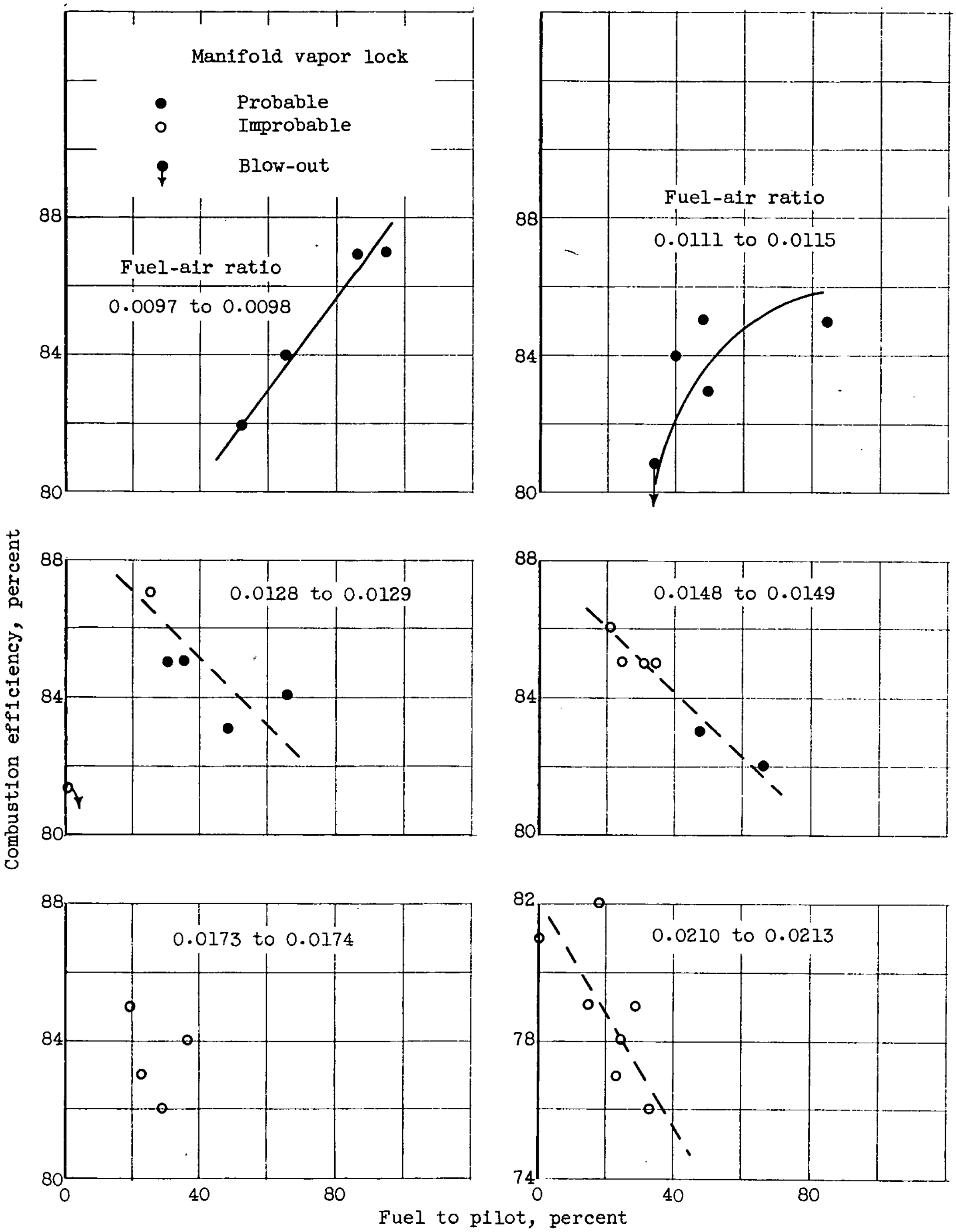


Figure 8. - Configuration of experimental combustor.



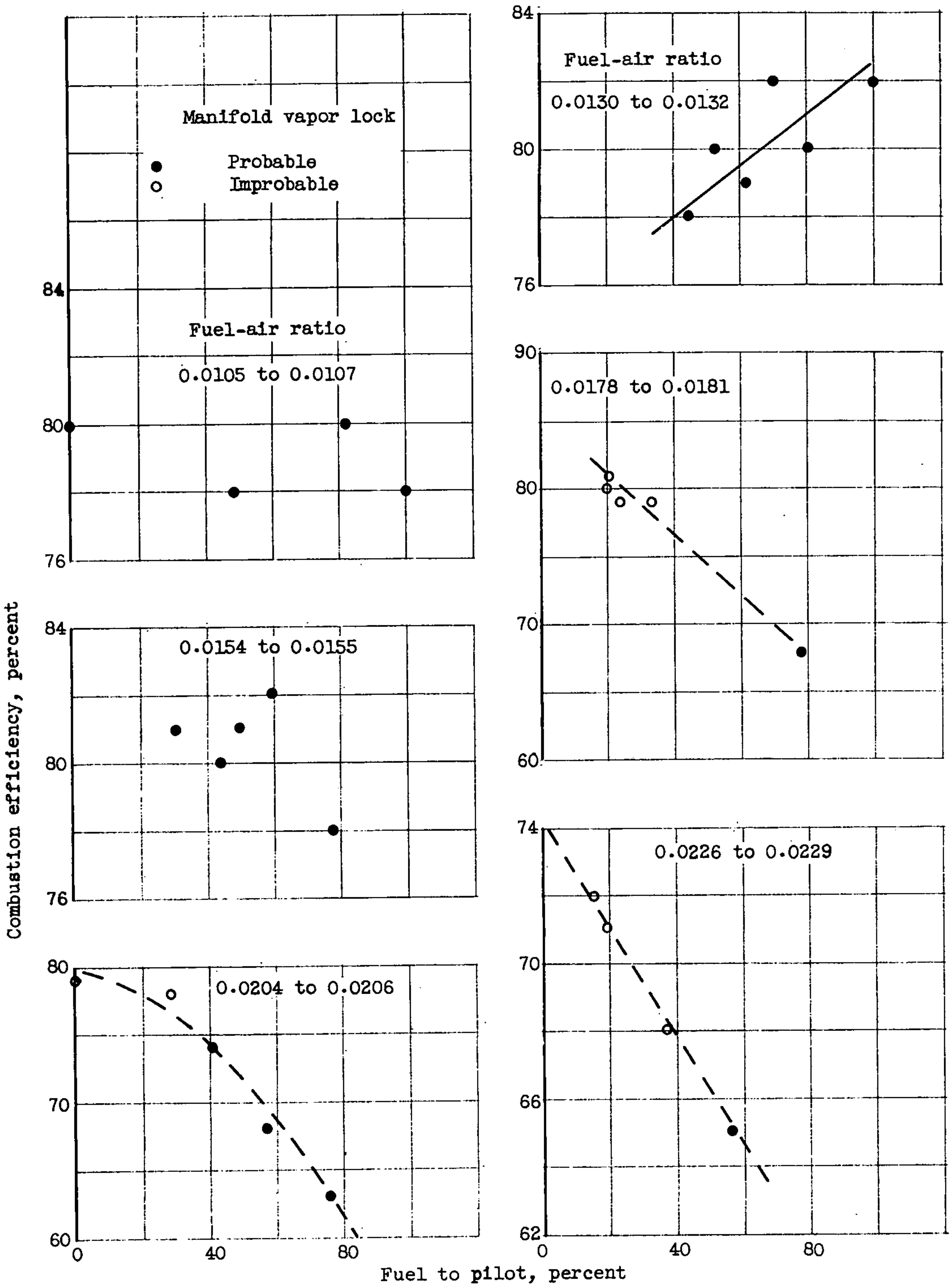
A 16 Swirl louvers, 1/2-in. diam. semicircle
B 13 Directional tubes, 5/8-in. diam.
C 8 Slots, 3/8 by 4 in.
D 8 Slots, 1 by 4 in.
E Pilot fuel supply
F Main fuel supply
G Observation positions

Figure 9. - Details of final configuration of experimental combustor.



(a) Test condition B: inlet pressure P_i, 8 inches of mercury absolute; inlet temperature T_i, 215° to 230° F; air flow W_a/A, 1.49 pounds per second per square foot.

Figure 10. - Efficiency of experimental combustor as function of percentage fuel flow to pilot for narrow ranges of fuel-air ratio.



(b) Test condition C: inlet pressure P_1, 6 inches of mercury absolute; inlet temperature T_1, 210° to 220° F; air flow W_a/A, 0.93 pounds per second per square foot.

Figure 10. - Concluded. Efficiency of experimental combustor as function of percentage fuel flow to pilot for narrow ranges of fuel-air ratio.

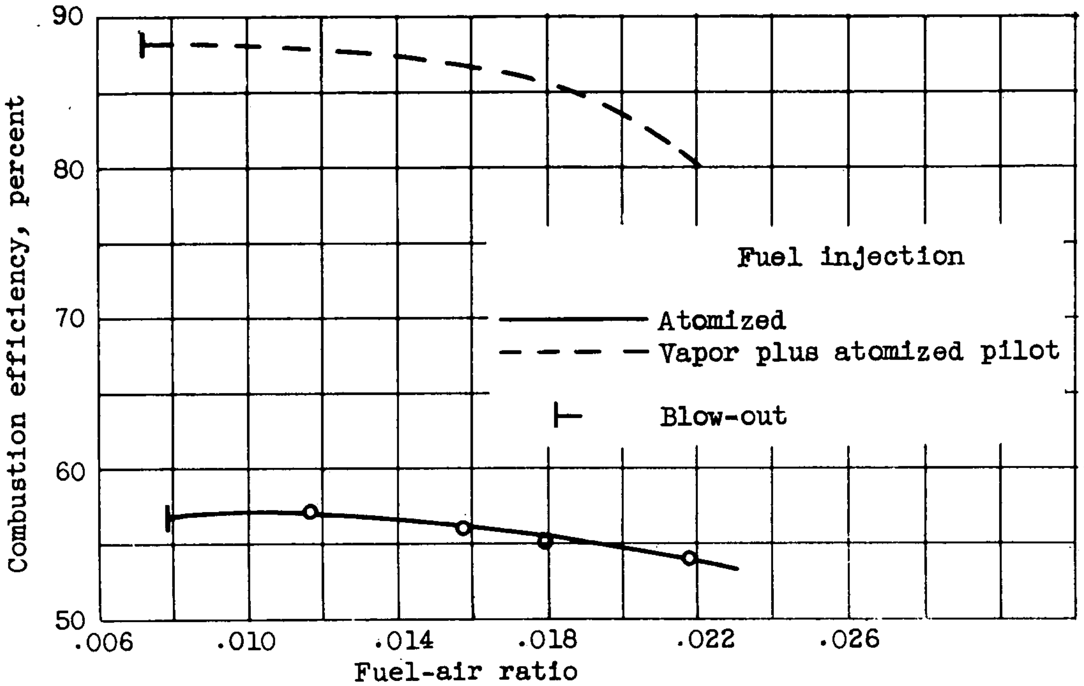
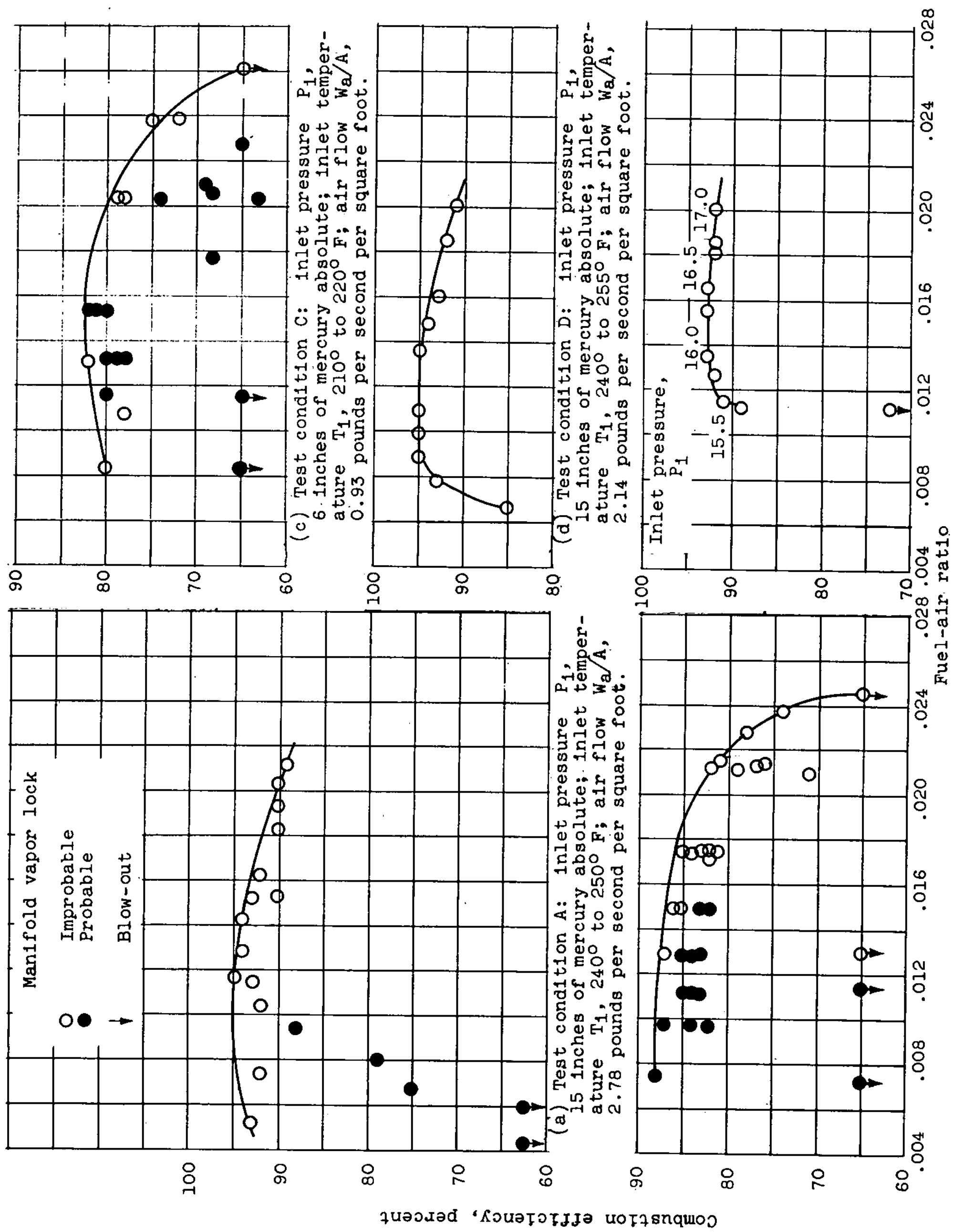


Figure 11. - Efficiency of experimental combustor with vapor injection plus atomizing pilot and with atomized fuel injection alone. Test condition B: inlet pressure P_1, 8 inches of mercury absolute; inlet temperature T_1, 215° to 230° F; air flow W_a/A, 1.49 pounds per second per square foot.



(a) Test condition A: inlet pressure P_1, 15 inches of mercury absolute; inlet temperature T_1, 240° to 250° F; air flow W_a/A, 2.78 pounds per second per square foot.

(b) Test condition B: inlet pressure P_1, 8 inches of mercury absolute; inlet temperature T_1, 215° to 230° F; air flow W_a/A, 1.49 pounds per second per square foot.

(c) Test condition C: inlet pressure P_1, 6 inches of mercury absolute; inlet temperature T_1, 210° to 220° F; air flow W_a/A, 0.93 pounds per second per square foot.

(d) Test condition D: inlet pressure P_1, 15 inches of mercury absolute; inlet temperature T_1, 240° to 255° F; air flow W_a/A, 2.14 pounds per second per square foot.

(e) Test condition E: inlet pressure P_1, 15.3 to 17.5 inches of mercury absolute; inlet temperature T_1, 255° F; air flow W_a/A, 3.62 pounds per second per square foot.

Figure 12. - Effect of fuel-air ratio on combustion efficiency of experimental combustor.

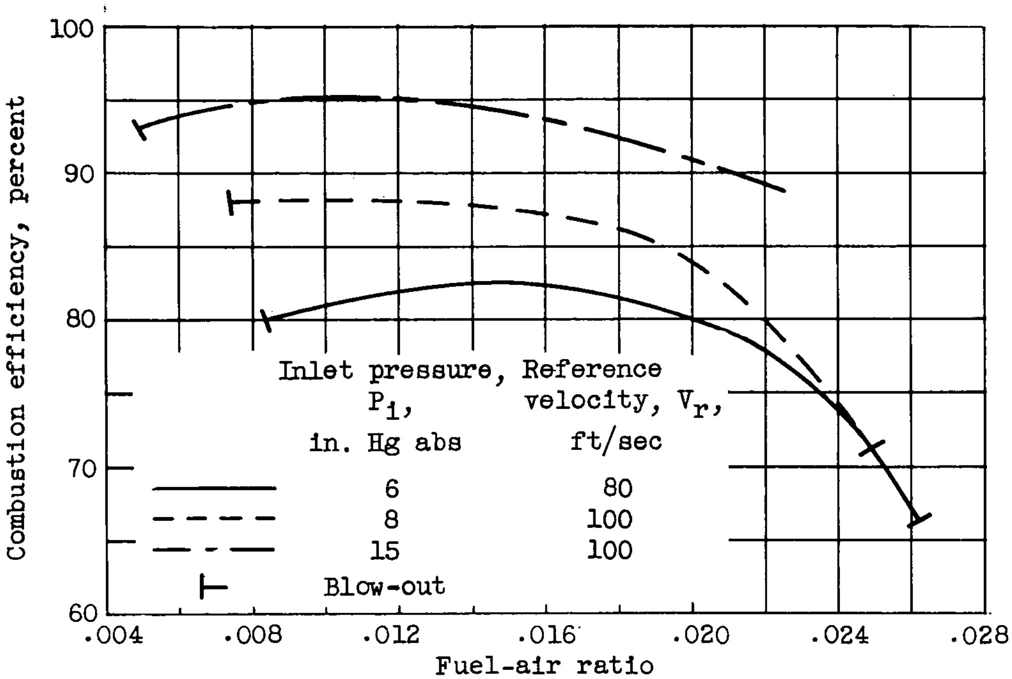


Figure 13. - Effect of pressure on combustion efficiency of experimental combustor.

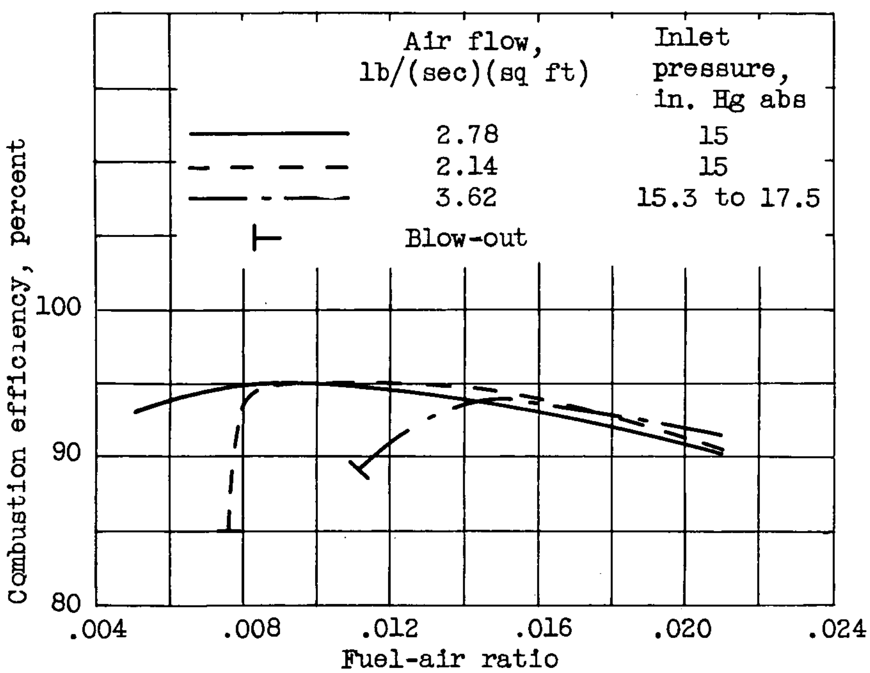
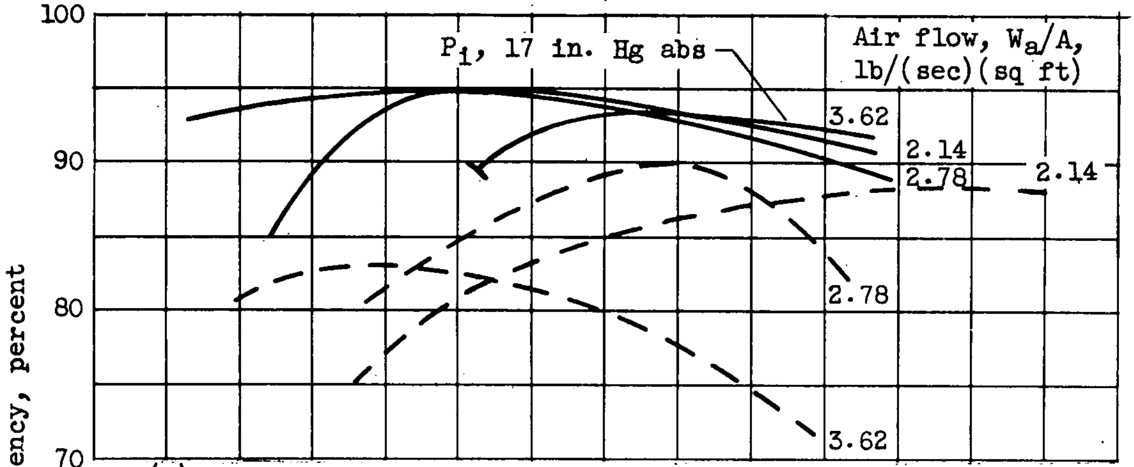
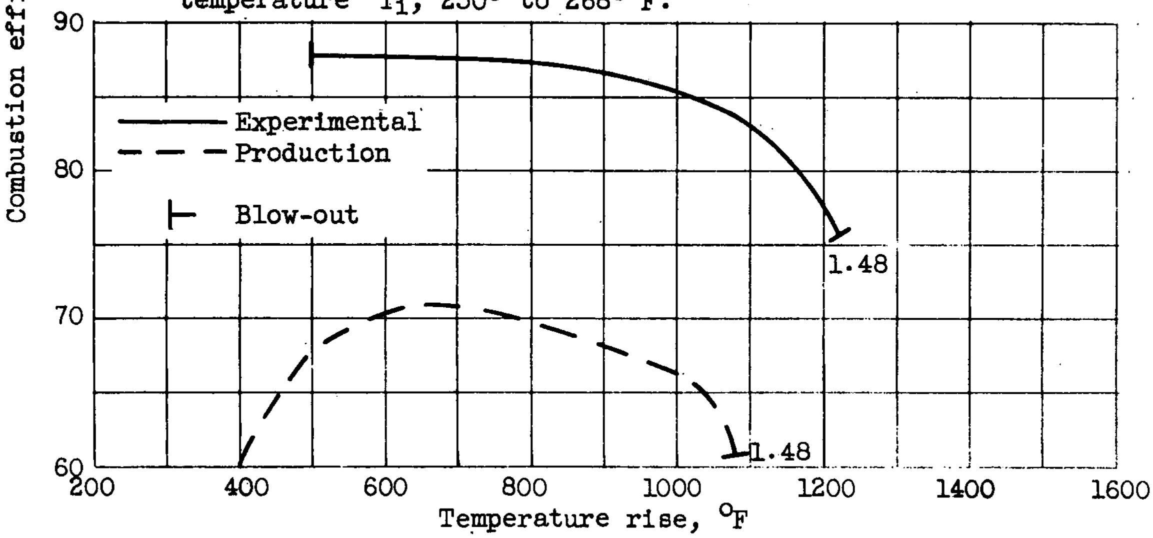


Figure 14. - Effect of mass-flow rate on efficiency of experimental combustor at near-constant pressure.



(a) Inlet pressure P_i, 15 inches of mercury absolute; inlet temperature T_i, 250° to 268° F.



(b) Inlet pressure P_i, 8 inches of mercury absolute; inlet temperature T_i, 225° to 268° F.

Figure 15. - Comparison of efficiencies of experimental and production combustors.

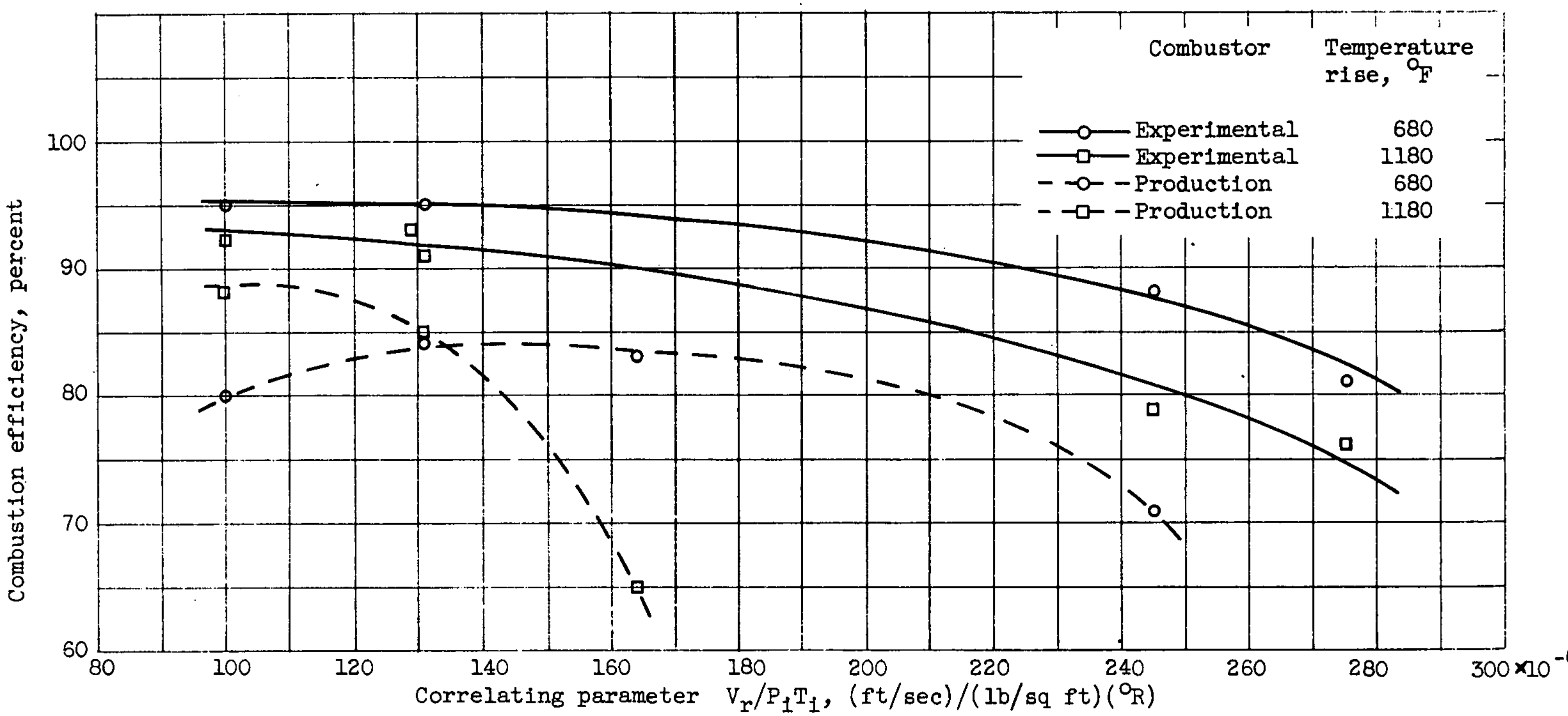


Figure 16. - Comparison of efficiencies of experimental and production combustors in terms of correlating parameter.

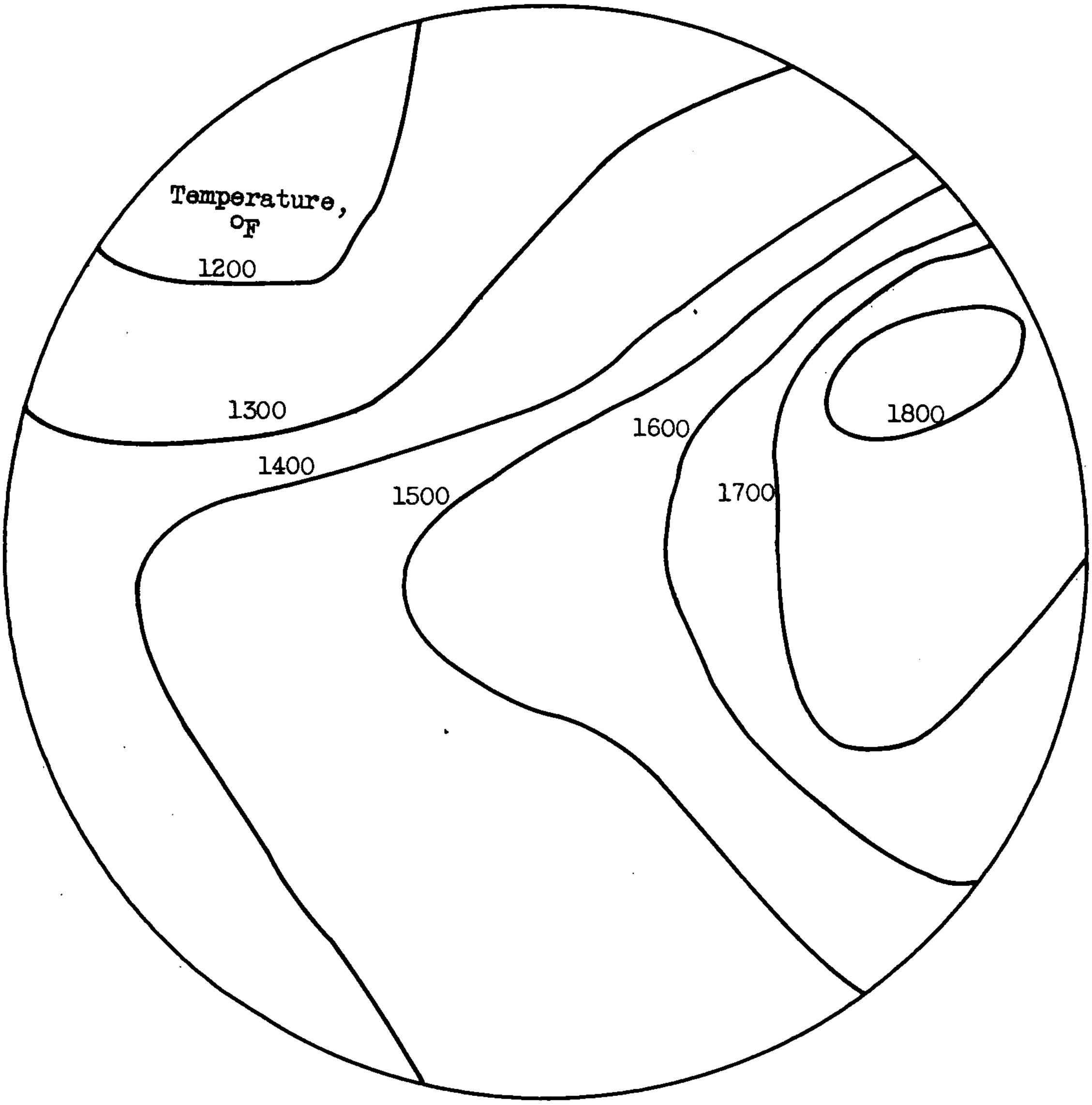


Figure 17. - Temperature profile of experimental combustor outlet. Average outlet temperature, 1475° F. Test condition A: inlet pressure P_i, 15 inches of mercury absolute; inlet temperature T_i, 240° to 250° F; air flow W_a/A, 2.75 pounds per second per square foot.